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Department of Electrical Engineering 37996
University of Tennessee, Knoxville, TN 2100

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This final scientific report describes basic research at the UTK Plasma Science Laboratory which was supported by the Air Force Office of Scientific Research, contract AFOSR 86-0100, with Dr. Robert J. Barker, Program Manager. During this three year period, 20 archival scientific papers were published, and 28 oral or poster conference papers were presented at the annual APS and IEEE plasma meetings. This contract also supported four graduate theses, 19 person-years of half time GRA research and training, and the preparation of 11 routine reports to the Air Force. These latter included three informal reports on our UTK-AFOSR summer undergraduate research fellowship program, two trip report on overseas lab visits and attendance at international plasma conferences, two progress/fc reports, two annual reports, a proposal, and this final report.

This contract has supported four research programs: 1) a program of research on plasma turbulence; 2) a program of research on plasma heating by collisional magnetic

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Dr. Robert J. Barker

22b. TELEPHONE (Include Area Code)
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FINAL SCIENTIFIC REPORT

"Heating, Instabilities, Turbulence, and RF Emission from Electric Field-Dominated Plasmas"

Covering the Period
March 15, 1986 to May 14, 1989

By

J. Reece Roth and Igor Alexeff
UTK Plasma Science Laboratory
Electrical & Computer Engineering Department
University of Tennessee
Knoxville, TN 37996-2100

Report PSL 89-2

Final Scientific Report

RESEARCH ON HEATING, INSTABILITIES, TURBULENCE, AND RF EMISSION FROM ELECTRIC FIELD DOMINATED PLASMAS

Submitted to

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

by

Prof. J. Reece Roth, Principal Investigator
Prof. Igor Alexeff, Co-Principal Investigator
UTK Plasma Science Laboratory
Department of Electrical & Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

for

Dr. Robert J. Barker
NP Program Manager
Air Force Office of Scientific Research
Bolling Air Force Base
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PRINCIPAL INVESTIGATOR: J. Reece Roth
Phone: (615) 974-4446 (Office)
(615) 974-6223 (Lab)

BUSINESS CONTACT: Mrs. Chris Cox
Phone: (615) 974-8159

Dr. J. Reece Roth
Principal Investigator

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ABSTRACT

This final scientific report describes basic research at the UTK Plasma Science Laboratory which was supported by the Air Force Office of Scientific Research, contract AFOSR 86-0100, with Dr. Robert J. Barker, Program Manager. During this three year period, 20 archival scientific papers were published, and 28 oral or poster conference papers were presented at the annual APS and IEEE plasma meetings. This contract also supported four graduate theses, 19 person-years of half time GRA research and training, and the preparation of 11 routine reports to the Air Force. These latter included three informal reports on our UTK-AFOSR summer undergraduate research fellowship program, two trip reports on overseas lab visits and attendance at international plasma conferences, two progress/forecast reports, two annual reports, a proposal, and this final report.

This contract has supported four research programs: 1) a program of research on plasma turbulence; 2) a program of research on plasma heating by collisional magnetic pumping; 3) a research program on the Orbitron submillimeter maser; and 4) the initial phases of a program on plasma cloaking of military targets for protection against radar and directed microwave energy weapons. Progress in these areas is documented in the text of this final report and in the twenty archival publications included in the appendices to this report. In addition to the above four research areas, we are continuing our work on plasma diagnostic development, and the development of new, state-of-the-art data analysis and reduction methods, including software development for online reduction of Langmuir probe, capacitive probe, and other diagnostic information. We are also developing the

capability to analyze electrostatic potential fluctuations by the methods of nonlinear dynamics. An important part of our research program has been the training of our graduate and undergraduate research assistants in state-of-the-art methods in the fields of high temperature plasma physics, plasma diagnostics, communications, and related areas.

EXECUTIVE SUMMARY

Background Information

This document describes a just-completed three-year program of research at the University of Tennessee's Plasma Science Laboratory, which is located on the Knoxville campus, and affiliated with the Electrical and Computer Engineerng Department. Our Laboratory specializes in the experimental investigation of interactions between RF radiation and plasmas, and in research in electric field dominated, steady-state plasmas. These plasmas exhibit several unique characteristics: very high levels of plasma turbulence; broad-band radio frequency emission; ion kinetic temperatures up to several kilovolts; ion kinetic temperatures much higher than that of the electron population; emission of millimeter and submillimeter microwave emission; and strong axial and radial electric fields, measured values of which have been in excess of several hundred volts per centimeter along the magnetic field. The presence of strong electric fields in the plasma allows work from external sources to be done on the plasma, thus affecting its RF emission, RF absorption, heating, and transport properties. Such electric field dominated plasmas can achieve high energy densities, and are of potential utility in such applications as lasers, pulsed broad-band radio frequency emitters, high power sub-millimeter microwave emission, communications, and cloaking of military targets against radar detection and microwave directed energy weapons.

Force Office of Scientific Research with the three-year contract AFOSR 89-0100, under the technical direction of Dr. Robert J. Barker, code NP, Physical Sciences division of AFOSR, Boling Air Force Base, Washington, DC. This three year contract covered four separately budgeted research areas, each of which was covered by a separate account within the University of Tennessee. The first account was a three-year research effort which covered plasma turbulence, plasma heating by collisional magnetic pumping, and preliminary research on plasma cloaking under Prof. J. Reece Roth; the second of four accounts supported research and development of the Orbitron microwave maser, by Prof. Igor Alexeff, who holds the basic patent on the Orbitron; a third account which funded the AFOSR-UTK Summer Undergraduate Research Fellowship Program for the summers of 1986, 1987, and 1988; and a fourth account, which, supported the computational physics effort of Dr. Robert J. Barker during the initial 18 months of this contract.

The level of effort on this contract during its three year duration is summarized on Table I. This contract was renewed at one year intervals in response to the initial proposal and two successive progress and forecast reports. These proposals followed up interesting results which appeared during the course of our exploratory research program, such as that on plasma cloaking during the latter phases of this three year contract. The period covered by this contract was from March 15, 1986 through May 14, 1989. This contract has been followed up by two successor contracts. In the case of Prof. J. Reece Roth's research, this was a two year contract, funded one year at a time, under the new contract number AFOSR - 89-0319, Dr. Robert J. Barker, Technical Program Manager. This new contract began on April 1, 1989, with

Prof. J. Reece Roth as Principal Investigator, and its title is "Electromagnetic Interactions with Magnetized Plasmas".

This contract supported the Principal Investigators for one quarter time during its entire duration. It also supported three graduate research assistants during the entire three years, with additional research assistants which were added during the second and third year of this contract when funds allowed. The total budget for this research program over its three year duration was $600,996, an amount which supported 4.0 person-years of full time equivalent effort by the Principal Investigators and faculty, and approximately 19 person-years of half time GRA research and training. The efforts of this research staff produced the twenty archival scientific papers listed in Appendix D, reprints of which are included in Appendix E of this report; and the 28 oral or poster papers at IEEE and APS plasma meetings which are listed in Appendix F, the abstracts of which are included in Appendix G of this report. In addition, the efforts of the AFOSR-supported research assistants in the UTK Plasma Science Laboratory produced four graduate theses, the title page and abstracts of which are included in Appendix H.

This AFOSR contract also supported a great many other activities, including particpation on national boards and committees by the Principal Investigators, invited talks, and travel to and participation in overseas international meetings. Documentation of some of these interactions by the Principal Investigators is included in Appendix I of this report. Trip reports on the international meetings and travel to foreign laboratories, which was supported by this contract, were submitted to the AFOSR shortly after they

took place. The text of these two trip reports is included in Appendix J of this report. The activities of each of the three years covered by this report have been documented in detail in annual reports, the UTK Plasma Science Laboratory report number of which is listed in Table 1. These reports have been submitted to the AFOSR and are available in its archives. In addition, each year of support required a proposal, included in a yearly progress and forecast report, the UTK report numbers of which are listed in the last column of Table I.

Objectives of Research

Three objectives were originally proposed for this three year research contract.

1. **A program of research in plasma turbulence.** The proposed research program in plasma turbulence built on some interesting observations made in the UTK Plasma Science Laboratory during exploratory research prior to the initiation of this three year contract. It was found that the plasma could be heated by actively coupling low frequency power from a sinusoidally perturbed "effector" probe into the plasma turbulence spectrum. It was also found that by varying the frequency and amplitude of the signal on the effector probe, it was possible to enhance the turbulent spectrum, giving rise to turbulent plasma heating, or to damp the turbulent spectrum at frequencies above 50 kilohertz, thereby reducing the rms level of turbulent fluctuations in the plasma by 10 to 20 dB. Our objective during this three year period was to learn more about plasma turbulence, turbulent mode coupling, and the nature of plasma turbulence itself by

TABLE I

MANPOWER ALLOCATION, BUDGETS, AND DOCUMENTATION

Year	Duration	Faculty/PI/Staff Full Time Equivalent Service, Months	GRA/Student 1/2-Time Service, Months	Yearly Budget	Annual Report UTK Number	Proposal or Progress/Forecast UTK Number
1	3/15/86-3/14/87 Roth Program	3 (Roth) 1.5(Rosenberg) 3 (Alexeff)	24	$74,994	PSL 87-5	PSL 86-2
	Alexeff Program	6.75 (Dyer)	4.5	$74.550	PSL 87-5	PSL 86-2
	Comp. Physics	- - -	- - -	$2,840	PSL 87-5	PSL 86-2
	Summer 1986 Fellowship Program	- - -	41.5	$20,556	PSL 87-5	PSL 86-2
	Sub-Total	14.25 months	70 months	$172,940		
2	3/15-87-3/14/88 Roth Program	3 (Roth) 1.5 (Rosenberg)	26	$87,344	PSL 88-4	PSL 87-6
	Alexeff Program	3 (Alexeff) 9 (Dyer)	6	$87,090	PSL 84-4	PSL 87-6
	Comp. Physics	---	---	$2,840	PSL 84-4	PSL 87-6
	Summer 1987 Fellowship Program		42	$20,556	PSL 84-4	PSL 87-6
	Sub-Total	16.5 months	74 months	$197,830		
3	3/15/88-5/14/89 Roth Program (12 months)	3 (Roth) 1.5 (Laroussi, Doctoral) 3 (Alexeff)	37	$101,185	This report PSL 89-2	PSL 88-7 PSL 88-7
	Alexeff Program (14 months)	9.75 (Dyer)	6.5	$99,541	PSL 89-2	PSL 88-7
	Sumer 1988 Fellowship Program	---	37	$29,500	PSL 89-2	PSL 88-7
	Sub-Total	17.25 months	80.5 months	$230,226		
	TOTAL	4.0 person-year	18.7 person years	P/Y $600,996		

developing state-of-the-art data handling systems which would improve our ability to make adequate measurements of turbulent plasma mode coupling. We also proposed to apply up-to-date methods to the analysis of plasma turbulence, including particularly the methods of nonlinear dynamics, commonly referred to as chaos theory.

2. A second major objective of our program was experimental research on collisional magnetic pumping. We proposed to develop the analytical theory of first order collisonal magnetic pumping, to check the analytical theory with a computational physics approach, and finally to test the theoretically predicted plasma heating rates experimentally with the AFOSR classical Penning discharge.

3. A second major objective of our program was research on the Orbitron submillimeter maser. The Orbitron research program investigated the instabilities that arise in a cloud of charged particles, electrons or ions, that orbit a charged wire. The program covered magnetic field effects, extension of investigations to three terahertz, and research on physical phenomena and steady state operation of the Orbitron submillimeter maser.

4. In addition to the above three objectives, which were part of the original research program, it became our objective in the third and last year of this program also to do preliminary experimental studies of plasma cloaking of military radar and directed microwave energy targets. This work evolved form the Principal Investigator's participation in a study workshop at the Air Force Geophysics Research Laboratory, where we put forward a plasma cloaking concept based on a plasma loaded dipolar magnetic field. Both Prof. Igor Alexeff and J. Reece Roth conceived independent approaches to plasma

cloaking during the final year of this program. Each of these approaches have been adopted by AFOSR in follow-on contracts.

Three-Year Technical Results

During the course of this three year research effort, the generosity of the Air Force Office of Scientific Research in supporting three or more graduate research assistants working under Profs. Roth and Alexeff, allowed each Principal Investigator to pursue more than one research topic at a given time, to maintain a critical mass of effort and students, to develop new diagnostic methods, and to pursue all of the major research objectives listed above to a resolution. Some topics on which we worked over this three year period led to new, interesting research results which represented a first-time contribution of its kind; some topics added to our stock of novel or unique diagnostic methods which contributed to Air Force contract research, as well as to the overall research program of the UTK Plasma Science Laboratory.

On the topic of collisional magnetic pumping, under the responsibility of Prof. J. Reece Roth, all of our initial objective were met. The technical outcome of the research program was gratifying, because we were not only able to show that first order collisional magnetic pumping is possible and that its heating rate is competitive with that of ion cyclotron resonance heating and other plasma heating methods, but also we were able experimentally to show that the predicted first order heating rates were consistent with our experiments on the classical Penning discharge in the UTK Plasma Science Laboratory. This three-year research effort started out by applying Floquet theory to the equations that describe the heating of a plasma by collisional

magnetic pumping. We recovered thirty-year-old results in the existing literature, for second order collisional magnetic heating with a sinusoidal magnetic pumping field, and then we were able to go beyond this to show that a sawtooth magnetic perturbation, with a magnetic field ramping up relatively slowly in time, and then droping off rapidly compared with the thermal equilibration time (or the collision time) of the plasma, would lead to first order heating. The magnitude of this heating, in electron volts per second, was comparable to that of other widely used RF plasma heating schemes such as electron or ion cyclotron resonance heating.

During the middle portion of this three year program, we were able to confirm, by a computational investigation, the analytical results on first order heating by collisional magnetic pumping. We were able to go beyond the small perturbation theoretical results with the computational investigations, to show the limitations of this small perturbation approach. This was done in such ways as determining the maximum perturbation amplitudes at which the first order heating would be possible, etc. Finally, we were able to develop a RF circuit which was capable of producing a sawtooth waveform of the magnetic field at frequencies ranging from 40 kilohertz to 200 kilohertz. This high power sawtooth generator was sufficient to perturb the background magnetic field by one percent or more, sufficient to yield measurable first order heating of the plasma electron population.

The results of our collisional magnetic pumping research were written up in a number of publications; these are listed in Appendix D as D1, 6, 8, 13 and to 15. The text of these archival publications are included at the end of this report. The oral and poster conference presentations resulting from our

research program on collisional magnetic pumping are listed in Appendix F, as F-2, 6, 12, 16, 19, 21, and 26. The abstracts of these conference presentations are listed in Appendix G, on the pages corresponding to the above numbers.

Our research program on turbulence and fluctuations in Penning discharge plasmas, under the responsibility of Prof. J. Reece Roth, started out with the development of a highly sophisticated two-channel amplifier and data handling system which was specially designed to have a cross-talk between the two channels of less than 40 dB. The development of this instrument was aimed at the problem of distinguishing cross talk between the data handling channels outside the plasma experiment, and mode coupling between two channels of data that occurred within the plasma as a result of plasma physical processes. When we use this instrument to study turbulence in two separate plasma channels, we can place an upper limit of 40 dB on the cross talk that is possible between two channels of information coming from the plasma. In the later stages of this three year program, we investigated plasma fluctuations and turbulence in the Penning discharge. An archival publication on this turbulence and fluctuation work is listed in Appendix D-7, a full length version of which may be found in Appendix E. The oral and poster conference presentations on this topic are listed in Appendix F, as F-7 and F8. Abstracts of these conference presentations may be found in Appendix G, on the page with the same number.

Our third research program on the Orbitron submillimeter microwave maser, under the direction of Prof. Igor Alexeff, achieved results in a number of areas, including operation of the Orbitron microwave maser in the steady

state, at high vacuum, and in diagnosing the properties of the Orbitron electron cloud and plasma with a variety of diagnostic methods. Some mechanisms of frequency bunching and RF emission were investigated during this three year period, and the influence of magnetic fields on the Orbitron operation were also investigated. Archival articles on the Orbitron research are listed in Appendix D as D-3, D-5, 9-12, 16, 18, and 19. A reprint of these archival publications may be found in Appendix E of this report. The oral and poster conference presentations on the Orbitron research program are listed in Appendix F, as F-4, 5, 9 to 11, 14, 15, 17, 18, 20, 23, 24, and 27. Abstracts of these oral or poster conference presentations are included in Appendix G, on pages with the same numbers quoted above.

Our exploratory research program on plasma cloaking began only 9 months before the end of this three year program, and is therefore not well represented by research publications. During this 9 month period, however, we were able to modify the magnetic field coil system that we had been using for Air Force research into a magnetic mirror configuration, and to propagate microwave radiation with frequencies between 4 and 10 gigahertz along the axis of the plasma. We found that the plasma would provide up to 20 dB of absorption of microwave energy, in a plasma in the 10^8 per cubic centimeter range of electron number densities. So much attenuation, over a broad frequency band from 4 to 10 gigahertz, and in so rarefied a plasma, was a good indication that this plasma cloaking concept was viable. This concept involves absorption at the electron gyrofrequency in a plasma confined in a spatially varying magnetic field. This should therefore be an interesting approach to shielding of military radar targets against radar scrutiny and

pulses from directed microwave energy weapons. The initial results of our experiments on plasma cloaking were presented at recent conferences. The abstracts of these poster presentations are listed in Appendix F, F-22 and 25. The one page abstracts of these conference presentations may be found in Appendix G, on pages with the same numbers.

Finally, during this three year research program other targets of opportunity arose from time to time which engaged the attention of either Prof. Igor Alexeff, Prof. J. Reece Roth, or both in collaboration. These topics included a simple MHD model for containment time scaling in tokamaks, an improved MHD model for the earth's magnetic field, a revised derivation of Landau damping, a visible plasma, (in which the effects of the electron plasma frequency in cesium becomes apparent at visible wavelengths), and a theory of plasma ion implantation for hardening metals. These miscellaneous topics have been written up for archival scientific journals, listed in Appendix D as D-2, 4, 17, and 20. The text of these archival publications may be found in Appendix E. The oral and poster conference presentations on these topics are listed in Appendix F, on pages 1, 3, 13, and 28. A one page abstract of these conference presentations is included in Appendix G, on pages with the same number.

In addition to the scientific objectives and their outcomes described above, this Air Force contract also served the secondary function of allowing the Principal Investigators to maintain the UTK Plasma Science Laboratory. Air Force funding, with additional support from the Office of Naval Research and the Army Research Office, has enabled us to become a Southeastern regional center of research in plasma science. A brochure on the activities of

the UTK Plasma Science Laboratory is included in Appendix B, and a listing of our Plasma Science Seminar series, with topics and speakers for the period of this three year contract, may be found in Appendix C. The UTK Plasma Science Laboratory has attracted media attention, thus giving exposure to AFOSR support of our activities. Some stories which appeared in local newspapers and newsletters are included in Appendix K of this report. It should be obvious from these stories that we have succeeded in building up a critical mass of students and faculty in the area of plasma science research, both basic and applied.

Results of Related Programs

This contract supported and benefited from other activities related to our experimental and theoretical research program. One such activity was the purchase of equipment, including low frequency and high frequency (microwave) network analyzers, with $233,745 of fiscal year 1985 funds which UTK was given by AFOSR under the Department of Defense-University Research Instrumentation Program (URIP). This equipment was delivered just prior to this three year contract period, and it made very substantial contributions to our research program, including developing the RF circuits for our collisional magnetic pumping research, the measurement of the effective electron collision frequency in our plasmas, and exploratory research on plasma cloaking. This equipment has given us experimental capabilities that are possessed by very few other university laboratories.

Another activity was participation by the principal investigators in international conferences in the field of microwave tube design (Igor Alexeff);

and the International Conference on Ionization Phenomena in Gases in 1987, and the Tokyo International Conference on Plasma Chemistry in September, 1987 (J. R. Roth). At least one archival paper describing research done under this AFOSR contract was presented at each of these meetings. An extensive trip report was submitted on the latter two conferences, which describe technical developments at the conference, and the Principal Investigator's visits to plasma-related laboratories before and after these conferences. Trip reports on these two conferences may be found in Appendix J.

Finally, this contract was used to partially support a pilot program, sponsored by AFOSR, to hire undergraduate students as research fellows affiliated with DoD contract research in the UTK Plasma Science Laboratory. During the three summers of 1986, 1987, and 1988, 28 students participated in this program. These students were from all over the United States, and most of them had grade point averages above 3.7. The program was very successful in terms of furthering the research objectives of our contract, and introducing students of engineering and physics to ongoing experimental research programs in the UTK Plasma Science Laboratory. Nearly all of these students have applied for and gone to graduate school in physics or engineering.

Utility of Results to the Air Force

The production and maintenance of steady state, high power density plasmas for such military purposes as weapons effects, high power lasers, and directed energy weapons may benefit from our observation and level of understanding of anomalous plasma resistivity due to plasma turbulence and

the effective collision frequency due to scattering of electrons off electric field fluctuations.

Another result of this program which may find application, in all branches of experimental plasma research, is the diagnostic we developed to measure the effective collision frequency of the electrons in plasmas which are subject to strong fluctuating electric fields. We have confirmed, as part of our ONR reearch program, the Galeev and Sagadeev theory for the effective plasma collision frequency, and demonstrated that their predicted functional scaling, as well as their quantitative prediction, agrees with the effective collision frequency measured in our highly turbulent Penning discharge plasmas. This increased understanding of the effective electron collision frequency in plasmas should make it possible to predict with confidence the level and scaling of all plasma transport coefficients which depend on the electron collision frequency in turbulent plasmas.

The Orbitron maser has been operated at wavelengths down to 0.3 millimeters in a pulsed mode, where the emitted power is about 1 watt. At lower frequencies, below 10 gigahertz, the Orbitron has been capable of producing more than one watt in the steady state. There appears to be no reason in principle why the Orbitron maser cannot be operated at a power of several hundred watts, or even kilowatts, at wavelengths below 1 millimeter. A large power output of sub-millimeter radiation could have several applications of interest to the Air Force, including seeing through dust and fog, high resolution radar, and propagation of intense beams of radiant energy over large distances.

It hardly seems necessary to elaborate on the desirability of making military targets disappear from radar screens, or shielding them from intense burst of microwave power from directed energy weapons. The research program which was initiated in the final year of this three year contract on plasma cloaking has demonstrated attenuations of up to 20 dB over a frequency range from 4 GHz to 10 GHz in a low density plasma confined in a mirror magnetic field. In the references listed in Appendix F, F-22 and F-25, we show that very large attenuations of microwave power are possible in low density plasmas, with relatively small columnar densities, providing only that they are in a magnetic field. In exploiting absorption at the electron cyclotron resonance frequency as a cloaking mechanism for microwave radiation, one should probably use a magnetic dipole as the magnetic containment configuration. The varying magnetic field in a dipole would allow a wide range of resonant frequencies, thus shielding such a satellite from a broad band of microwave frequencies.

Finally, there are only a handful of ways in which plasma can be heated to high power density. We have recently demonstrated in the UTK Plasma Science Laboratory, for the first time, the experimental heating of a plasma by collisional magnetic pumping. Our archival reprints on plasma heating by collisional magnetic pumping may be found listed in Appendix D, on pages D-1, 6, 8, 13 to 15. These reprints are included in their entirety in Appendix E. This heating method allows coupling RF energy to plasmas without the use of electrodes in contact with them. This new addition to known plasma heating techniques may be of value to the Air Force for applications requiring high power density or high energy density plasmas, including plasma cloaking,

high power lasers, plasma materials processing of exotic aerospace materials, and other applications in which high power densities or high levels of plasma purity are required.

THE UTK PLASMA SCIENCE LABORATORY

Scope of Research Programs

Course offerings and active research in the field of plasma science have been underway at the University of Tennessee, Knoxville, since 1970. The UTK Plasma Science Laboratory was set up in its present form in 1980, and occupies the entire first floor of Ferris Hall, the Electrical Engineering Department's building on the UTK campus. Using our ONR contract as a legal vehicle, the UTK Plasma Science Laboratory acquired in 1980 approximately $400,000 of plasma-related instrumentation from the NASA Lewis Research Center, which enabled us to begin a research program on electric field-dominated plasmas. This inventory of laboratory equipment has been supplemented over the last several years by used, but serviceable, surplus equipment obtained from Department of Defense installations within a half-day's driving distance of Knoxville.

The UTK Plasma Science Laboratory is equipped with a variety of operating plasma diagnostic instruments, and a large inventory of power supplies, electronic test equipment, and RF and communications-related electronic equipment and hardware which supported our exploratory research efforts. The UTK Plasma Science Laboratory also has two inexpensive-to-operate steady state Penning discharge plasmas on which instruments can be developed and debugged, and on which data of unusually high quality can be taken with our existing instruments. A grant of FY 1985 funds amounting to $233,743 from AFOSR under the DoD-University Research Instrumentation Program (URIP), has allowed us to purchase state-of-the-art RF network analyzers and other state-of-the-art electronic test equipment which not only

provides our students training with the latest equipment, but also allows us to take plasma diagnostic data of a quality and kind that is possible to very few other university-based research laboratories.

Since 1980, the UTK Plasma Science Laboratory has been partially supported on a continuing basis by contracts with Office of Naval Research and the Air Force Office of Scientific Research, and on an occasional basis by the Army Research Office, the National Science Foundation, and the Tennessee Valley Authority. In calendar year 1988, the total budget of the UTK Plasma Lab was just under $300,000. The UTK Plasma Science Laboratory is affiliated with the Electrical and Computer Engineering Department of the University of Tennessee in Knoxville, and focusses its research efforts on steady-state, electric field-dominated plasmas. Our emphasis on steady state plasmas makes it much easier for us to take diagnostic data of high quality, and to vary parameters in an exploratory way to identify and study the physical processes which occur in these plasmas. The emphasis on electric field dominated plasmas (those plasmas having strong radial and/or axial electric fields penetrating them) has allowed us to focus on areas of plasma science which has been neglected both within the DoE's fusion program, and by other university research groups in the field of plasma science. Particular electric field dominated plasmas under study in the UTK Plasma Science Laboratory include Prof. Igor Alexeff's AFOSR-supported work under this contract on the Orbitron maser, which is of interest because of its capability to produce sub-millimeter microwave emission at power levels in excess of one watt; and plasmas generated by Penning discharges, which are highly turbulent, and provide a convenient test bed for research on plasma

turbulence, anomalous electrical resistivity, collisional magnetic pumping, and such industrially relevant applications as our work on corrosion inhibition of metals by plasma ion implantation, for the Army Research Office.

Laboratory Space and Utilities

The UTK Plasma Science Laboratory occupies approximately 1800 sq. ft. on the ground floor of Ferris Hall on the UTK campus. This floor also has offices available with six desks for research assistants associated with the Laboratory, and a loading dock for equipment. The Laboratory is furnished with running water, two sets of two inch supply and discharge mains at city water pressure for cooling of the magnetic field coils; city sewers; 70 KVA of 440 volt three-phase electrical power; 120 KVA of three-phase, 220 volt electrical power, fluorescent lighting, air condtioning, tile floors, and building services. In addition, the Plasma Science Laboratory has available approximately 400 sq. ft. of office and light-duty research space on the 5th floor of South Stadium Hall,under the nearby football stadium.

The Electrical Engineering Department offers further services and facilities, including a student machine shop, an electronic parts store, a technical services shop which can maintain and repair equipment, secretarial services, a photo-copy machine, a Xerox 8010 Star word processor with a laser printer, and a wide range of computational facilities.

The impact of AFOSR support on the UTK Plasma Science Laboratory can be seen by comparing Figure 1 with Figure 2 below. On Figure 1, 2 is shown the UTK Plasma Science Laboratory in late 1980, before the start of AFOSR funding. The coils, which had been obtained surplus from the Oak

FIGURE 1

Figure 2

Ridge National Laboratory, are at the center of the floor. Figure 2 is a recent photograph of the AFOSR equipment shown in Figure 1, with the magnetic field coils and several other diagnostic systems in place.

Impact of DoD-URIP Equipment Grant

In 1983 we submitted a proposal to the AFOSR for $233,743 to buy new, state-of-the-art equipment for our AFOSR research effort in the UTK Plasma Science Laboratory. Most of this money was to be spent on low-and high frequency network analyzers, to make possible highly sophisticated active and passive plasma diagnostics. In April, 1984, we were pleased to learn that this proposal was fully funded with fiscal year 1985 money. This money became available to us in January, 1985.

According to the Hewlett Packard representative, the network analyzers which we purchased represent the most sophisticated and highest-tech item in the Hewlett Packard equipment inventory. In order to operate this equipment, Prof. Rosenberg and one of our graduate research assistants from the UTK Plasma Science Lab took a special course in Atlanta, Georgia, in August, 1985. The new instrumentation has greatly facilitated the measurement of RF emissions above 1 gigahertz, and makes possible quantitative measurements, which heretofore have been extremely difficult, at frequencies up to 18 GHz.

The Hewlett-Packard network analyzers have played a central role in the AFOSR research program since they became available in late 1985. Our HP model 8510 microwave network analyzer has been used to measure the absorption of microwave radiation at the electron cyclotron resonance

frequency, information which allows us to determine experimentally the effective collision frequency in our plasma. The low frequency network analyzer has also been useful in measuring the power spectrum of electrostatic potential fluctuations and electron number density fluctuations in our plasma, data which are necessary for experimental comparison with the Galeev-Sagdeev theory for the effective collision frequency due to fluctuating electric fields in a plasma. The 80 dB dynamic range and absolute calibration of these instruments have made them particularly useful in our research on collisional magnetic pumping and plasma cloaking.

Specalized Research Equipment Used on This Contract

Over the past nine years, the UTK Plasma Science Laboratory has built up an inventory of specialized research equipment, plasma diagnostic instrumentation, and computerized data reduction capabilities that are, if not unique, at least well above average by university standards. Among the specialized equipment at the UTK Plasma Science Laboratory available for our research program are the following:

1. A 20 centimeter inside bore, 0.35 tesla, 18-coil, water-cooled solenoid complete with power supply, cooling water, and a control system capable of providing steady state magnetic fields for plasma research. This facility is shown in Figure 3, and is currently dedicated to the ONR Research Program.
2. A 17 centimeter inside diameter, 0.50 tesla, 8 coil water-cooled solenoid, with power supply, cooling water, and control system. This facility shown in Figures 1 and 2, is used in the current AFOSR research contract for the classical Penning discharge, and is capable of providing a steady state magnetic field for plasma research.

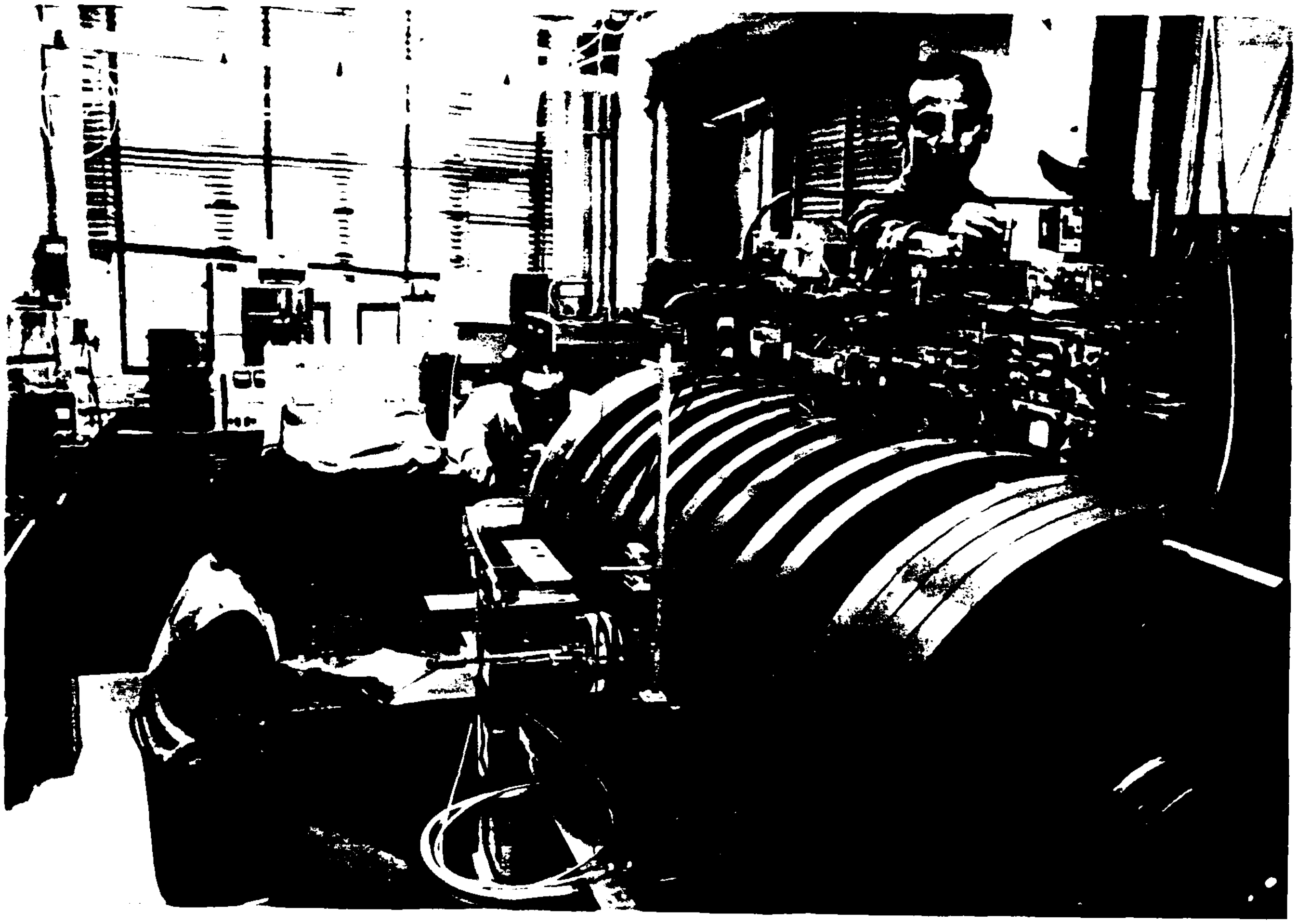


Figure 3

3. Both of the above mentioned magnet systems are furnished with glass vacuum systems, which allow flexibility in rearranging diagnostic probes and sensors. The glass vacuum systems also allow electrostatic potential fluctuations and RF emissions from the plasma to be detected outside the vacuum system. Each of these vacuum systems has a refrigerated cold trap, using a special freon which achieves -130 °C, and each system can reach base pressures in the mid or low 10^{-6} torr range. Each vacuum system also has a turbo-molecular vacuum pump which reduces the background contamination which would otherwise occur from diffusion pump oil. These vacuum systems have been in operation for several years, are throughly debugged, and are extremely reliable research tools.

4. The UTK Plasma Science Laboratory has available a 40 kilovolt, 1 amp dc high voltage power supply which is used to energize the Penning discharges on our current contracts. This power supply has safety interlocks, overcurrent and overvoltage trip protection, and allows the output voltage to be varied from a few hundred volts to a maximum value of 40 kilovolts, while drawing up to 1 amp of current. This power supply uses vacuum tube electronics, and therefore operates reliably in spite of the occasional arcs characteristic of steady state Penning discharge plasmas.

5. A major recent addition to our inventory of specialized research equipment is a Hewlett-Packard model 8510 high frequency network analyzer which is capable of operating from 45 MHz to 18 GHz. This network analyzer is shown in Figure 4, and was purchased with part of our AFOSR-DoD-University Research Instrumentation Program grant awarded to the UTK Plasma Science Laboratory. This analyzer allows us to measure the frequency

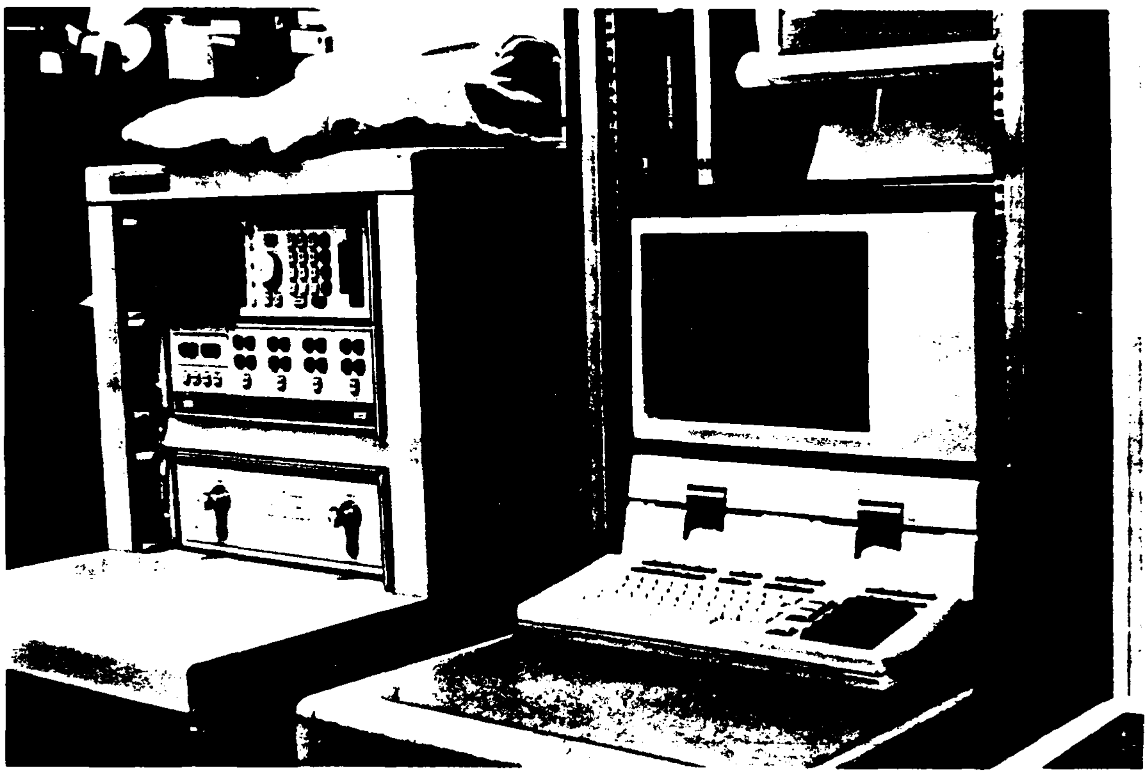


Figure 4

response and impedance function of microwave equipment over the frequency range of the instrument. It facilitates absolute measurements of RF power, and turbulence measurements over a dynamic range of 80 dB. Very few other university-based plasma research laboratories in the country possesses such an instrument.

6 As part of the instrumentation purchased with the AFOSR-DoD-University Research Instrumentation Program grant, we also bought a Hewlett Packard model 3577 low frequency network analyzer, the frequency response of which ranges from 5 Hz to 200 MHz. This network analyzer can be used for calibration of absolute signal levels, and for measuring the frequency response of our diagnostic equipment. It too, has a dynamic range of 80dB.

Plasma Diagnostic Instrumentation

During the past nine years, the UTK Plasma Science Laboratory has built up an inventory of plasma diagnostic instrumentation which makes it well-equipped by university standards. Some of this instrumentation is the first of its kind and has been documented in the literature. Such publications are listed in Appendices D and F. The most notable items of our diagnostic instrumentation are the following:

1. Vacuum Mass Spectrometer - The vacuum system used for the classical Penning discharge is equipped with a vacuum mass spectrometer which not only allows us to detect leaks in the vacuum system, but also confirms that the gas in the vacuum system during an experiment is that intended.

2. Capacitive Probes - We have developed a dual channel capacitive probe system complete with cables, amplifiers, filters and shields. The entire system has a frequency response which is virtually flat from 1 kilohertz to 10

megahertz. These probes can be positioned at various locations immediately outside the glass vacuum system, where they can detect the electrostatic potential fluctuations associated with plasma instabilities and turbulence. Under other conditions of operation, capacitive probes are inserted into the vacuum system, and are positioned in the vicinity of the plasma boundary.

3. Langmuir Probes - The UTK Plasma Science Laboratory has a number of Langmuir probes and a high voltage Langmuir probe power supply system which is used for measuring plasma parameters. An unusual problem encountered in these electric field dominated plasmas is that the plasma potential is often quite high, on the order of kilovolts. For this reason, it is necessary to bias the Langmuir probe to several kilovolts in order to take a Langmuir probe curve which will allow us to measure the electron kinetic temperature and number density. We have developed a data handling system which will take the Langmuir probe traces automatically, and print out, on line, the plasma parameters based on the Langmuir probe trace. This software development is described in the next section.

4. Retarding Potential Energy Analyzers - The vacuum system used for the classical Penning discharge has a retarding potential energy analyzer permanently installed. When data are taken, this analyzer is energized by an external power supply on an equipment rack. The retarding potential energy analyzer is used to measure the integrated energy distribution function of ions lost along the axis of the magnetic field in the two Penning discharges.

5. A Polarization Diplexing Microwave Interferometer - This instrument was developed in collaboration with Prof. Andrew L. Gardner of Brigham Young University. This instrument can use both modes of polarization of the

microwave radiation at 28 GHz, and can detect densities as low as 10^8 electrons per cubic centimeter.

6. Analog-to-Digital Data Handling System - The UTK Plasma Science Laboratory has an analog-to-digital data handling system based on three LeCroy Model 8837, 32 megahertz transient recorders interfaced to an IBM AT computer. This AT computer was furnished by our AFOSR contract during this three-year contract period. This system is capable of taking three simultaneous channels of data, and digitizing them at rates up to 32 MHz. This digitized data can be displayed on the screen of the IBM AT computer, and then can be sent by a hard-wire data link to the Electrical Engineering Department's VAX 780-11 computer for analysis by approxpriate software programs, or analyzed on-line by the AT computer.

7. Calibrated, Broadband Antennas - As part of our on-going research program to measure RF plasma emissions, we have developed two calibrated, broadband antennae, which have a very broad and flat frequency response, from approximately 100 MHz to 1.0 GHz. In addition, they have been absolutely calibrated to measure the incident power, in watts, received from our plasmas. The instrumentation and hardware necessary to make and implement these absolute calibrations have also been developed, and include the HP 3577 low frequency network analyzer, described in the previous section.

8. Other Research Equipment - In addition to the above individual items of plasma diagnostic equipment, the UTK Plasma Science Laboratory is well equipped with a variety of power supplies, RF voltmeters, signal generators, microwave hardware and accessories, and other equipment necessary to do RF

detection and plasma research. Over the years, we have built up our inventory of research equipment through the DoD Surplus Property Utilization Program, which makes available used but serviceable equipment to DoD contractors. This has allowed us to obtain euqipmnt for exploratory research which we could not afford otherwise.

Specialized Data Reduction Capabilities

At the UTK Plasma Science Laboratory, we have attempted to stay at the leading edge of the development of plasma diagnostic software and digital data handling and reduction methods. The resources of our Electrical and Computer Engineering Department are very valuable in this respect. Some of the hardware and software which we employ are as follows:

1. The VAX 780-11 Computer - This computer is installed in Ferris Hall, and is readily available to users in the Electrical Engineering Department. There are four hardwired data links from the VAX computer to the UTK Plasma Science Laboratory, three of which are presently connected to terminals and/or the minicomputers described below. This computer makes available on-line data reduction of fairly sophisticated programs, the running of which on our minicomputers in the Plasma Lab would either take too long, or not be possible.
2. A HP 9836 Series 200 Minicomputer - The primary function of this unit is to run the HP 3577 and HP 8510 network analyzers in their fully automated mode. It can also be used as a stand-alone computer for other data handling and data processing tasks. This computer is connected by a hardwired link to the EE Department's VAX 780-11 mainframe computer.

3. A LeCroy 3500 SA Minicomputer - This LeCroy Minicomputer was used as a three channel, 32 MHz transient recorder and digitizer system with three LeCroy model 8837 transient recorders. In addition, the LeCroy system also has a four channel, 1 MHz model 8501 analog-to-digital converter which was used at lower frequencies, when the system was used as a smart X-Y plotter or oscilloscope. The LeCroy 3500 SA minicomputer was connected by a hardwired data link to the EE Department's VAX 780-11 mainframe computer, and could transmit digitized data to that computer for analysis by various software programs. After about 5 years of use in our research program, this unit was retired from service in late 1988 because of its limited capabilities when compared to the IBM AT system described below.

4. An IBM AT Minicomputer Based Data Handling and Reduction System - In early 1987, an IBM-AT computer complete with an extensive software library and a color printer became available to UTK Plasma Science Laboratory through our AFOSR research contract. In order to take advantage of the on-line data reduction capabilities which this AT computer made possible, we purchased an interface which allowed us to use our LeCroy Model 8837 transient recorders and the LeCroy Model 8501 low frequency transient recorders with the AT computer. This arrangement allowed us to take data from capacitive probes or other transient signals related to plasma parameters, digitize them, and put them directly on analysis programs built into the IBM AT computer. This made it possible to reduce, for example, our fluctuating potential data using the methods of chaos dynamics on the AT computer, without requiring the ECE Department's mainframe VAX 780-11 mainframe computer. The new LeCroy-AT transient recording, data

handling, and data reduction system allowed a great deal more flexibility than the previous arrangement with the LeCroy 3500 computer, including limited on-line data reduction and much shorter data turnaround times.

5. Dynamical Systems, Inc. Nonlinear Dynamics Software Program - In order to apply recently developed advances in chaos theory and nonlinear dynamics to our plasma fluctuation data, we obtained a commercially available software program from Dynamical Systems, Inc. of Tucson, Arizona. This program is capable of taking a time series from a fluctuating quantity, such as the electrostatic potential fluctuations at the edge of a plasma, or the number density fluctuations within a plasma. The software package contains routines which plot in two or three dimensions, calculate Fourier spectra, reconstruct phase portraits, take Poincare sections, compute correlation dimensions, compute Lyapunov exponents, and perform various other data manipulations. This Dynamical Systems software program has allowed us, with a minimum investment of time in software development, to apply the powerful methods of nonlinear dynamics and chaos theory to the problem of understanding plasma turbulence and fluctuations in our Penning discharge plasmas.

6. Software for Plasma Turbulence Analysis - The software required to analyze the statistical properties of simultaneously sampled signals is based on a time series analysis computer program very generously furnished to us by Prof. E. J. Powers of the University of Texas, Austin. This program has been modified for use on the EE Department's VAX 780-11 mainframe computer. This program has the capability of displaying such statistical properties of the plasma fluctuations as the auto and cross power spectra of two simultaneously sampled channels, phase spectra of the fluctuations

between two channels, the coherence spectra, and finally it also contains the output software package required to plot the calculated data.

7. Computerized Reduction of Langmuir Probe and Retarding Potential Energy Analyzer Data - The LeCroy model 8501 transient recorder system has been modified to interface with the IBM AT Computer, and act as a smart X-Y plotter, to do real time, on-line data reduction from such diagnostic instruments as Langmuir probes, retarding potential energy analyzers, capacitive probes,and charge exchange neutral energy analyzers. The software required to support this and similar plasma diagnostic data reduction systems was not available from LeCroy or any other manufacturer. Mr. Saeid Shariati, a former graduate student in the Department of Electrical Engineering (who now works for the General Electric aircraft engine plant in Cincinatti, Ohio), has, for his master's thesis, developed software for the LeCroy 3500 transient recorder system which reduces data from a retarding potential energy anayzer and the high voltage Langmuir probe system, as well as our charge-exchange neutral energy analyzer system. This software is now in the process of being modified for the IBM AT computer.

Weekly Plasma Seminar

An important part of our research activities at the UTK Plasma Science Laboratory is a weekly Plasma Seminar in which the senior faculty and all research assistants participate, along with undergraduate students and any one else who is interested. Our graduate research assistants are expected to give at least one hour-long seminar on their work during each semester. In addition, we obtain outside speakers from the Oak Ridge National Laboratory

or visitors to the campus to supplement our seminar schedule. The nature of this weekly seminar can best be appreciated by looking over some of the topics which were covered in recent academic years covered by this contract. Copies of our Plasma Seminar schedule are included in Appendix C of this report.

RESULTS OF RESEARCH PROGRAM

Predecessor Research Funded by AFOSR

The three year program of research described in this report was a combination of two previous AFOSR research contracts which had been separately funded, with Profs. J. Reece Roth and Igor Alexeff at the UTK Plasma Science Laboratory. The three year program of research described in this report represents a separately funded and independently peer reviewed effort from the earlier contracts of Prof. Roth and Alexeff, which it combines.

Prof. Roth's predecessor contract was AFOSR-81-0093 (ROTH) which started on May 15, 1981, and terminated on March 14, 1986. This five year program of research was described in Final Scientific Report PSL 86-1, which is in the AFOSR archives. This contract, in its latter stages, was under the technical supervision of Dr. Robert J. Barker of AFOSR. This contract was followed, without interruption of funding or research activity in relevant areas, on March 15, 1986 by the work described in this report.

This earlier contract was concerned with the investigation of physical processes in an electric field dominated plasma produced by steady state operation of a classical Penning discharge with an approximately uniform axial magnetic field profile. It is this device, a photograph of which is shown in Figure 2. The phenomena of particular interest in this investigation were anomalous plasma resistivity, axial electric field profiles, plasma turbulence, turbulent heating of ions, nonlinear phenomena relating to energy dissipation in the plasma, and the initial phases of research on plasma heating by collisional magnetic pumping. This preceeding work on collisional magnetic

pumping and plasma turbulence was continued into the three year program of research described in this report.

Also prior to the initiation of this three year research program, Prof. Igor Alexeff of the UTK Department of Electrical and Computer Engineering held contract AFOSR 82-0045, which also terminated on March 14, 1986. This contract covered the development of a submillimeter microwave emitter based on the Orbitron configuration. Prof. Alexeff holds a U.S. Patent on this device, and under AFOSR sponsorship, analyzed its operation and instabilities theoretically, while pursuing an experimental program which has achieved steady state operation of the Orbitron, and generated wavelengths down to 0.3 millimeters, or 1 TeraHertz. The Orbitron configuration attracted interest at the Naval Research Laboratory, at Hughes Research Laboratory, and other places where advanced research on microwave emitters is conducted. This work on the Orbitron microwave emitter was continued in the separately funded and peer reviewed research program incorporated into the three year program described in this final scientific report.

Objectives of Research Program

The objectives of this research program initially were to follow up some of the more interesting observations made in the predecessor program described above, and to investigate, in an exploratory way, new and interesting phenomena that became apparent during the course of our research activities.

1. In the area of the Orbitron microwave emitter, Prof. Igor Alexeff proposed to do further research on the Orbitron submillimeter maser in order to better understand the physical process responsible for emission, particularly under conditions that lead to high power output. It was intended to explore some of the instabilities and the physics of the radio frequency emission process in the theoretical program originally proposed. This has been done in the archival and conference papers listed in Appendices D and F. Prof. Alexeff also proposed an experimental program to investigate the physical processes which limit the frequency obtainable from Orbitron masers operated in the steady state. It was expected that further insights into the physics and technology of short wavelength RF emission would emerge, which could push the frequency limit of the Orbitron below the limit of 0.3 millimeters, a limit established by the capabilities of the detector in our laboratory and not of the Orbitron microwave emitter itself.

2. Prof. Roth originally proposed two research programs, one relating to plasma heating and one to plasma turbulence. The proposed research program in plasma turbulence had as an objective the investigation of conditions under which nonlinear mode coupling is possible in the turbulent spectrum, between a driving frequency and the background noise. This nonlinear mode coupling can be responsible for significant turbulent heating of plasmas. We also proposed to follow up some earlier observations made under our ONR contract, in which an external signal at a frequency well below the characteristic plasma resonance frequencies apparently interfered with nonlinear mode coupling in the turbulent spectrum. As a result of this interference, the level of turbulence in the plasma was reduced by up to 20 dB

below its undisturbed background level due to self-excited modes. We originally proposed to investigate the physical mechanism responsible for this supression of the turbulent spectrum. Understanding of this turbulent suppression could have wide implications, if the effect is not restricted to plasmas; aircraft wings and ship hulls for which the level of turbulent viscosity was suppressed by up to 20 dB would surely be subject to much less drag than those subject to normal turbulent eddy formation. In the event, our ONR contract was funded in parallel with the AFOSR contract, and much of the proposed research on plasma turbulence was done under that contract and not charged to the AFOSR. The very interesting results of this ONR work have been summarized recently in a final report on a nine year program of research for the ONR, recently distributed as UTK Report PSL 89-1. The proposed research on plasma turbulence for the AFOSR evolved into investigation of interaction of electromagnetic radiation with magnetized plasmas, which led to our present AFOSR contract on plasma cloaking.

The second research program originally proposed for this three year period by Prof. Roth involved a new approach to collisional magnetic pumping. Collisional magnetic pumping was first suggested as a plasma heating method in the late 1950's, but it was never carried beyond the early theoretical investigations, as a result of the rather low plasma heating rates predicted by the approach discussed at that early time. The perturbation of a plasma confined in a background magnetic field by a sinusoidal waveform results in a collisional magnetic heating effect which is second order in the magnetic perturbation; this heating rate was too low to be competitive with other plasma heating mechanisms known at that time. Prof. Roth and his

Ph.D. student, Mounir Laroussi, found an approach which is theoretically predicted to result in a heating rate proportional to the first power of the magnetic perturbation, a rate about 200 to 300 times higher than that predicted in the earlier papers for the second order heating effect. The proposed research program on collisional magnetic pumping consisted of a theoretical research program designed to explore this new approach to collisional magnetic pumping, and also designed to obtain theoretical expressions for the plasma heating rate in terms of plasma parameters which can be checked against experimental measurements made in the UTK Plasma Science Laboratory. The proposed experimental research program consisted of an attempt to heat a steady state plasma in a classical Penning discharge using collisional magnetic pumping. All of these objectives were achieved, and are described in archival papers and conference presentations listed in Appendices D and F.

Finally, during the last year of this three year contact period, our research on the effective collision frequency in plasmas, and on the interaction of electromagnetic radiation with magnetized plasmas, led us to propose a new mechanism for plasma cloaking based on the absorption of radar and other microwave energy at the electron cyclotron frequency in magnetized plasmas. It became our objective to investigate whether a broad range of microwave frequencies used in military radar systems could be absorbed by a low density Penning discharge plasma in a variable magnetic field, the strength of which was chosen to correspond to military radar frequencies.

The generosity of AFOSR in funding two independent research programs under Profs. Alexeff and Roth, and in allowing us to hire more than two

GRA's, allowed us to pursue more than one of these objectives simultaneously. It was not uncommon for two or more of the scientific objectives to be pursued in parallel while at the same time new plasma diagnostic methods were being developed. The relatively long period of consistent AFOSR funding allowed us to pursue nearly all of these objectives to a resolution and/or final publication.

Accomplishments of the First Year Research Program, March 15, 1986 to March 14, 1987

This section of the report will discuss the progress made during the first year of this research program, from the inception of contract AFOSR 86-0100 on March 15, 1986, to March 14, 1987. Unless noted otherwise, the activities described below were completed within budget and on schedule. There were no cost overruns or unexpended funds at the end of this contract year.

Collisional Magnetic Pumping Research

Our research program on plasma heating by collisional magnetic pumping research remained on schedule this year. Mr. Mounir Laroussi, our senior graduate research assistant on the Air Force contract, passed his Ph.D. comprehensive examination in June, 1986, and required only the successful completion of the Ph.D. oral exam on his thesis research to finish his degree program.

The theoretical portion of Mr. Laroussi's research on collisional magnetic pumping was essentially completed, and contains both analytical and computational physics proofs that first order plasma heating can result from collisional magnetic pumping when the excitation coil is properly

energized. Much of his theoretical work was presented at the 18th Southeastern Symposium on Systems Theory (which had an archival proceedings), in Knoxville, Tennessee on April, 1986, (paper D-1 in Appendix D) and at the IEEE meeting in Saskatoon, Canada, in May, 1986. (Paper F-2, in Appendix F, an abstract of which is on page G-2 of Appendix G).

The experimental part of our collisional magnetic pumping research program was well underway during this year. During the summer of 1986, a group of AFOSR undergraduate research assistants characterized the plasma generated by the classical Penning discharge used in the AFOSR research program, in such a way as to provide input data for the collisional magnetic pumping research. This appeared as F-8 in Appendix F, an abstract of which is on page G-8 of Appendix F. The special amplifiers and other hardware needed to excite the magnetic pumping coil were fabricated and tested. Some of the design information was presented at the 28th Annual Meeting of the APS Plasma Physics Division in November, 1986, in Abstract F-6 of Appendix F, which is included on page G-6 of Appendix G.

Plasma Turbulence Research

No plasma turbulence research was originally proposed for the first of the three years in this experimental program. However, Mr. John E. Crowley, our second graduate research assistant supported by the AFOSR, did a Master's thesis project which will be very useful for future experimental turbulence research. Mr. Crowley finished the design and construction of a two-channel spectrum analyzer system which, combined with the low frequency HP network analyzer, can measure nonlinear mode coupling

between two frequencies with an instrumental-cross-talk between the two channels that is at least 40 dB below typical signal levels. This instrument will give us a capability in experimental plasma turbulence research that is probably unique in the world. When other investigators of plasma turbulence insert two or more probes into a plasma, they often see non-linear mode coupling between frequencies picked up by their probes. There are at least two possible sources of any nonlinear mode coupling observed between frequencies in such experiments: 1. The non linear mode coupling can result from nonlinear processes in the plasma itself; or 2. The observed mode coupling can result from cross-talk between the two channels of information being processed by the experimental instruments. With the two channel spectrum analyzer system developed by Mr. Crowley, we can be confident that the nonlinear mode coupling we observe is due to the plasma, and that the cross-talk between channels is at least 40 dB below the typical signal levels seen in our turbulence experiments. A description of Mr. Crowley's instrument, along with examples of its functioning, was presented at the APS Plasma Physics meeting in November, 1986, an abstract of which is listed as F-7 of Appendix F, and included on page G-7 of Appendix G.

Mr. John E. Crowley completed the two channel spectrum analyzer system and took a job in the aerospace industry in March, 1987. Mr. Crowley was replaced as the junior graduate research assistant on the Air Force contract by Mr. Scott Stafford, a B.S. graduate of Tennessee Technological University, who has a career interest in plasma research. Mr. Stafford started his tenure as a graduate research assistant on Monday, September 22, 1986. Mr. Stafford assisted Mr. Laroussi in taking data on collisional magnetic

pumping, while at the same time positioning himself to begin an experimental research program in plasma turbulence. Mr. Stafford began his experimental program of plasma turbulence research in September, 1987, in the second year of the three-year program.

Orbitron Research

The first year of this contract resulted in several notable advances. The most unusual is the development of a new high-pass filter for millimeter and sub-millimeter radiation that is both very useful in our research, and promises to be of great utility in the field of microwave research as a whole. A patent application has been filed for this device.

A listing of our recent research successes is given below:

a. New sharp-cut-off filter.

The new filter is needed because in this very short wavelength region, standard microwave waveguides become too attenuating, and quasi-optical methods are necessary. Thus, mirrors are used to direct and focus the radiation. Even plastic lenses are too attenuating. For measuring frequencies, grating spectrometers are used, while for bandpass selection, wire meshes are used. (We just received a briefing on this from the millimeter microwave group at Princeton.)

We have been using wire meshes for bandpass selection in our research work. However, these meshes do not have a sharp cut-off with decreasing frequency, so we find difficulty in deciding if we are observing a weak, high-frequency signal, or the bleed-through of a strong, low-frequency signal.

Consequently we have designed a new filter that has a cut-off with decreasing frequency that is about 10 to 100 times sharper than the meshes and also seems to cause little insertion loss. These filters have allowed us to make remarkable progress in our microwave research. In addition, they should be very useful in the work of others as we know of no such devices in the literature. The filters basically are a two-dimensional mesh of short microwave waveguides. Since they are waveguides, they have a sharp and controllable cut-off. However, since they are short, they do not have the strong absorption that standard waveguides do. Also, since they comprise a two-dimensional plane matrix, they transmit plane waves as plane waves (reciprocity) without the need for input or output couplers. These latter two features are unique, and are the basis for a patent.

b. New fabrication process for sub-millimeter tubes.

The sub-millimeter tubes that we have been fabricating require the insertion and handling of wires that are smaller than one thousandth of an inch in diameter. Formerly, we had severe kinking and breaking problems during construction. We now have a new fabrication technique that does not require the wire to pass through holes, or to be attached to supports. The wire is merely laid across an edge, and is fastened with epoxy cement. We can insert or replace a wire in such a tube in a few minutes. In addition, the tubes are now metal cylinders with a plastic window at both ends. This special construction allows us to pass a probing beam from an external microwave oscillator through the tube while it is in operation to study the process of microwave emission. (See below.)

c. Verifying that plasma processes are not necessary in Orbitron emission.

According to Schumacher and Harvey at the Hughes Research Laboratories, our pulsed tubes emit microwaves by the second-harmonic emission from the plasma produced during the discharge. Their model fails for our new, double-window tubes, because we have passed an unperturbed probing microwave beam through an operating Orbitron when it is emitting frequencies up to three times higher than the probing beam. In this work, we have used our new, sharp cut-off filters to verify that we really do have the high frequency emission.

Other experiments that also suggest that the Hughes plasma model is inappropriate for Orbitron emission are as follows; Schumacher states that the plasma emission occurs because two interpenetrating electron beams from opposite sides of the microwave tube interact in the plasma. However, we covered most of the inside of a tube with the insulating plastic, mylar, so that only one beam could be present, and found that the tube still emitted microwaves at almost the same power level. In addition, we did x-ray studies of an operating tube, and found intense x-ray emission from the central wire. This suggests that the central wire is not at plasma potential, as suggested by Hughes, but is much more positive. Finally, we replaced the wire with a small plate, so that electron orbits could not occur. According to Hughes, the orbits are not needed, only a small anode is required for microwave emission. However, for our "wire-less" tube, the emission essentially ceased.

d. Evaluating the Upward Frequency Chirp in Orbitron Emission

The equation predicting Orbitron frequency for circular orbits is given below,

$$\omega = \frac{1}{2}\left(\frac{-zeV}{m\,\ell n\,\frac{r_2}{r_1}}\right)^{1/2}.$$

Here, ω is the emitted frequency (radians/second), r is the orbit radius (meters), z is the charge state of the electron (-1), e is the magnitude of the coulomb charge (1.60×10^{-19}), V is the positive voltage applied to the wire, m is the electron mass (kilograms), and r_2 and r_1 are the radius of the Orbitron cathode and anode respectively (meters).

Schumacher and Harvey have pointed out that experimentally the frequency chirps upward in time, while the voltage decreases, and claim that the orbit frequency is invalid. However, this statement ignores the negative - mass feature of the Orbitron, which requires an upward - frequency chirp during emission. This feature is quantitatively computed below.

Let us differentiate the equation for frequency

$$\frac{d\omega}{dt} = \frac{\partial\omega}{\partial r}\frac{\partial r}{\partial t} + \frac{\partial\omega}{\partial V}\frac{\partial V}{\partial t}.$$

The first term is ignored by Schumacher and Harvey, who only computed the second.

$$\frac{d\omega}{dt} = \left(\frac{zeV}{m \ln \frac{r_2}{r_1}} \right)^{1/2} \left(- \frac{1}{r^2} \frac{dr}{dt} \right) + \frac{1}{r} \left(\frac{ze}{m \ln \frac{r_2}{r_1}} \right)^{1/2} \left(V \frac{dV}{dt} \right)$$

$$\frac{d\omega}{dt} = - \omega \left(\frac{1}{r_2} \frac{dr}{dt} \right) + \frac{1}{2} \omega \left(\frac{1}{V} \frac{dV}{dt} \right) .$$

As dr/dt and dV/dt are both negative, the first term produces an upward frequency chirp, while the lower produces a downward frequency chirp.

The term dV/dt is simply measured. The term dr/dt is computed as follows: The emitted microwave power must be released by a cloud of trapped electrons dropping through a potential well. If the power emitted is W, we find

$$W = nZeE \frac{dr}{dt} .$$

We know E in the emitting region from the emitted frequency. We estimate n to be the largest number of electrons capable of being trapped. We then find dr/dt to give an upward frequency chirp in excellent agreement with observations, and about a hundred times higher than the downward frequency chirp given by dV/dt, which it overwhelms. Using a smaller value of n gives an even larger frequency chirp, which does not fit observations. Using a larger value of n is not realistic-it conflicts with the laws of electrostatics. Consequently, we feel this computation is the correct one.

5. Summer Students

Our summer students of 1986 made strong contributions to our Orbitron project. These advances are tabulated below.

1. Electron confinement along a long wire. (Brent Zitting).

   We demonstrated that electrons could be trapped around and propagate along a wire about 2 meters long. A defect in the wire was observed to disrupt confinement (loss of angular momentum).

2. Computer simulation of instability. (John Wysor). A computer code was created to simulate a multi-particle instability. The result was made into an 8-mm movie.

3. Ion confinement around a wire. (Lance Bledsoe). The polarity of the device was reversed to trap ions in orbit. By suddenly terminating the voltage, the ions were released, and their energy was measured by time-of-flight. An absence of high energy ions revealed an expected absence of ions from very small orbits.

Computational Physics Support

This activity, originally budgeted for $2000 during this first year of the contract, was utilized as intended. During this time, Dr. Barker required some software and instruction manuals, which cost $550. This was procured, charged to this account within the contract, and sent to him. With Dr. Barker's approval, the remaining funds in this $2000 budget line item were used to support the Undergraduate Research Fellowship Program and/or to support graduate research assistant salaries, in view of an unanticipated 15% increase in tuition and fees not originally budgeted.

1986 Summer Undergraduate Research Fellowship Program

The AFOSR summer undergraduate research assistantship program for 1986 was extremely successful. We had altogether 10 undergraduate students participating in the program, 9 of whom were supported by the Air Force, and one of them (not a U.S. citizen) was supported by the Office of Naval Research contract of which J. R. Roth is Principal Investigator.

We sent out announcements and application blanks for the program in early March, 1986, with an April 1 deadline. We had 26 applications from an excellent group of engineering students, more than half of whom had grade point averages above 3.5 out of a scale of 4.0. One disappointing feature was that the salary offered, $600 per month, originally budgeted, attracted only four applicants from off the UTK campus, and only one of these four actually participated in the program.

The students arrived on campus and started their summer activities on Monday, June 16, 1986. During the first two weeks, Professor Roth gave a series of lectures to orient the students to the field of plasma science, to laboratory research, and to the AFOSR research program at the UTK Plasma Science Laboratory. During the third week of the program, a series of equipment tutorials were given by the senior graduate research assistants to the students. These were hands-on demonstrations of how to use some of the more sophisticated diagnostic, data handling and electronic test instruments in the Plasma Laboratory. These students took advantage of the opportunity to use our equipment and, with one exception, were anxious to obtain hands-on experience in the Plasma Lab.

During the period from mid-July to early September, a series of lectures by senior faculty of the UTK Electrical and Computer Engineering Department were scheduled to introduce these summer students to graduate study and research invarious areas of electrical engineering. Finally, during the last few days of this program, from Wednesday, September 17 to Friday, September 19, 1986, the undergraduate research assistants gave half-hour oral presentations describing their work. Before completing their summer's activities, they also prepared written documentation of their summer research project.

These AFOSR undergraduate summer research assistants were asked to spend 20% of their time on routine housekeeping activities to improve the working environment of the UTK Plasma Science Laboratory, and 80% of their time on a single research project that would be their responsibility. All of the summer undergraduate research assistants who are UTK electrical engineering students elected to hand in the documentation of their summer research project for a grade and academic credit in a senior laboratory project course. Copies of the students' program evaluation forms, and of the write-ups of their summer projects, were forwarded to Dr. Barker of AFOSR as an informal document at the end of the summer.

Accomplishments of the Second Year, March 15, 1987 to March 14, 1988

This section will discuss progress made from the beginning of the second year of the contract on March 15, 1987, to March 14, 1988. Unless noted otherwise, the activities discussed below were within budget and on schedule.

Collisional Magnetic Pumping Research

Our research program on plasma heating by collisional magnetic pumping had a major success during this report period, when electron heating attributable to collisional magnetic pumping was experimentally observed. To my knowledge (JRR), this is the first time that plasma heating by collisional magnetic pumping has been observed experimentally. The only attempts of which I am aware to implement this plasma heating scheme experimentally were made in the late 1950's at the Princeton Plasma Physics Laboratory. Their attempt to heat plasmas in this way failed, apparently because the application of collisional magnetic pumping disturbed the confinement in the stellarator plasma on which it was attempted, and so degraded the density and confinement time of the plasma that the heating effect could not be observed. The heating which we have observed resulted from first order heating of a sawtooth wave perturbation of the background magnetic field.

The experimental measurements described in the above paragraph were made by Dr. Mounir Laroussi, the senior graduate research assistant working on our AFOSR contract, who received his Ph.D. on June 1, 1988. His Ph.D. thesis contains the analytical theory of first and second order collisional magnetic pumping; a computational physics study of first order plasma heating by collisional magnetic pumping; and experimental data on both second order plasma heating (by a sinusoidal perturbation of the magnetic field) and first order plasma heating (by a sawtooth, unidirectional current flow in the driving coil). A photograph of the apparatus is shown in Figure 4.

The theoretical and computational portions of Dr. Laroussi's thesis research contain proofs that first order plasma heating can result from collisional magnetic pumping when the excitation coil is properly energized. His theoretical and computational work was presented at two major conferences during the period covered by this report; He presented a paper at the 7th APS Topical Conference on Applications of Radio Frequency Power to Plasmas in Kissimmee, Florida from the 4th to the 6th of May 1987. A reprint of this paper is included in appendix E, starting on page E-23. A second paper emphasizing potential industrial applications of plasma heating by collisional magnetic pumping was presented at the 8th International Symposium on Plasma Chemistry in Tokyo, Japan, August 31 to September 4, 1987. A reprint of this paper is included in Appendix E of this report, starting on page E-29. A trip report on this conference is included in Appendix J.

The experimental portion of our collisional magnetic pumping research program was assisted by our junior graduate research assistants, Mr. Scott A. Stafford and Mr. Min Wu. Several of our summer undergraduate research fellows worked with Dr. Laroussi in designing and testing the solid state circuit required to create a unidirectional current waveform in the exciting coil at frequencies up to several megahertz. This was a challenging job at the power levels, up to 200 watts, demanded by this application, and both Mr. Laroussi, our GRA's, and the summer research fellows learned a great deal about high power, high frequency solid state electronic switching circuits. One of these summer students, Mr. Kenneth Swayne, presented his summer work as a paper at the IEEE Region 3 Student Conference in April, 1988, and placed third out of 17 schools competing.

Plasma Turbulence Research

In March, 1987, Mr. John E. Crowley, a graduate research assistant who was supported by the AFOSR, submitted an excellent Master's thesis entitled "Conversion of the HP3577A Network Analyzer to a Spectrum Analyzer Mode of Operation with Low Noise and Cross-talk". Mr. Crowley completed the design and construction of a two-channel spectrum analyzer system which, combined with our low frequency HP network analyzer, can measure nonlinear mode coupling between two frequencies with an instrumental cross-talk between the two channels that is at least 40 dB below typical signal levels from the plasma.

This instrument gives us a capability in experimental plasma turbulence research that is probably unique in the world. When other investigators of plasma turbulence insert two or more probes into a plasma, they often see nonlinear mode coupling between frequencies picked up by their probes. There are at least two possible sources of any nonlinear mode coupling observed between frequencies in such turbulence experiments: 1) The nonlinear mode coupling can result from nonlinear processes in the plasma itself; or 2) The observed mode coupling can result from cross-talk between the two channels of information being processed by the experimental instruments. With the two channel spectrum analyzer system which was developed by Mr. Crowley, we can be confident that the nonlinear mode coupling we observe is due to the plasma, and that the cross-talk between channels is at least 40 dB below the typical signal levels seen in our turbulence experiments. An Abstract and Table of Contents of Mr. Crowley's thesis is included as Appendix H of this report.

Orbitron Research

During the period from March 15, 1987 to March 14, 1988, we consolidated our Orbitron research program, submitting three papers and one book chapter for publication. These are listed in Appendix D, as Nos. 9 to 12, and their reprints are in Appendix E, on pages E-35, E-40, E-47, and E-55. Prof. Igor Alexeff attended the Polytechnic University in New York to give a lecture on Orbitrons, and to start a cooperative venture with AFOSR-supported universities. The Orbitron research program carried on a successful summer activity with the Air Force-supported Summer Research Fellows. Prof. Alexeff traveled to mainland China to give an invited paper on Orbitrons at the Chengdu Institute for Radio Research, and to explore the possibility of setting up some joint research ventures. Simultaneously, the plasma lab staff associated with the Orbitron project attended the June IEEE International Conference on Plasma Science in Crystal City, Virginia, to give additional papers on our Orbitron research. These papers are listed in Appendix F, and their abstracts are in Appendix G, on pages G-14 and G-15. During this period, Prof. Igor Alexeff received the IEEE Region 3 (Southeastern United States) Outstanding Engineer award in April, 1987.

Some of our research highlights during this period are listed below:

1. We developed a high-power pulsed gas-filled Orbitron. We used multiple anode wires to accomplish this. In previous multiple-wire Orbitrons, each wire would fire separately, causing several small pulses instead of one large one. In this device, the wires were so placed, that an avalanche on one would spread to all, causing them to fire together.

2. We developed a hot-cathode vacuum Orbitron in which the entire cavity resonator the anode - is incandescent. This was an attempt to improve current feed for increased power and higher-frequency performance. It seems to work very well. See the photo in Figure 5.

3. We redid a computer program to solve the quartic equation (used in beam-plasma computations). It not only runs well, but is 16 times faster (no approximations) than commercial programs. Figure 6 is a photograph of Prof. Alexeff and Fred Dyer making measurements relevant to the Orbitron.

Figure 5

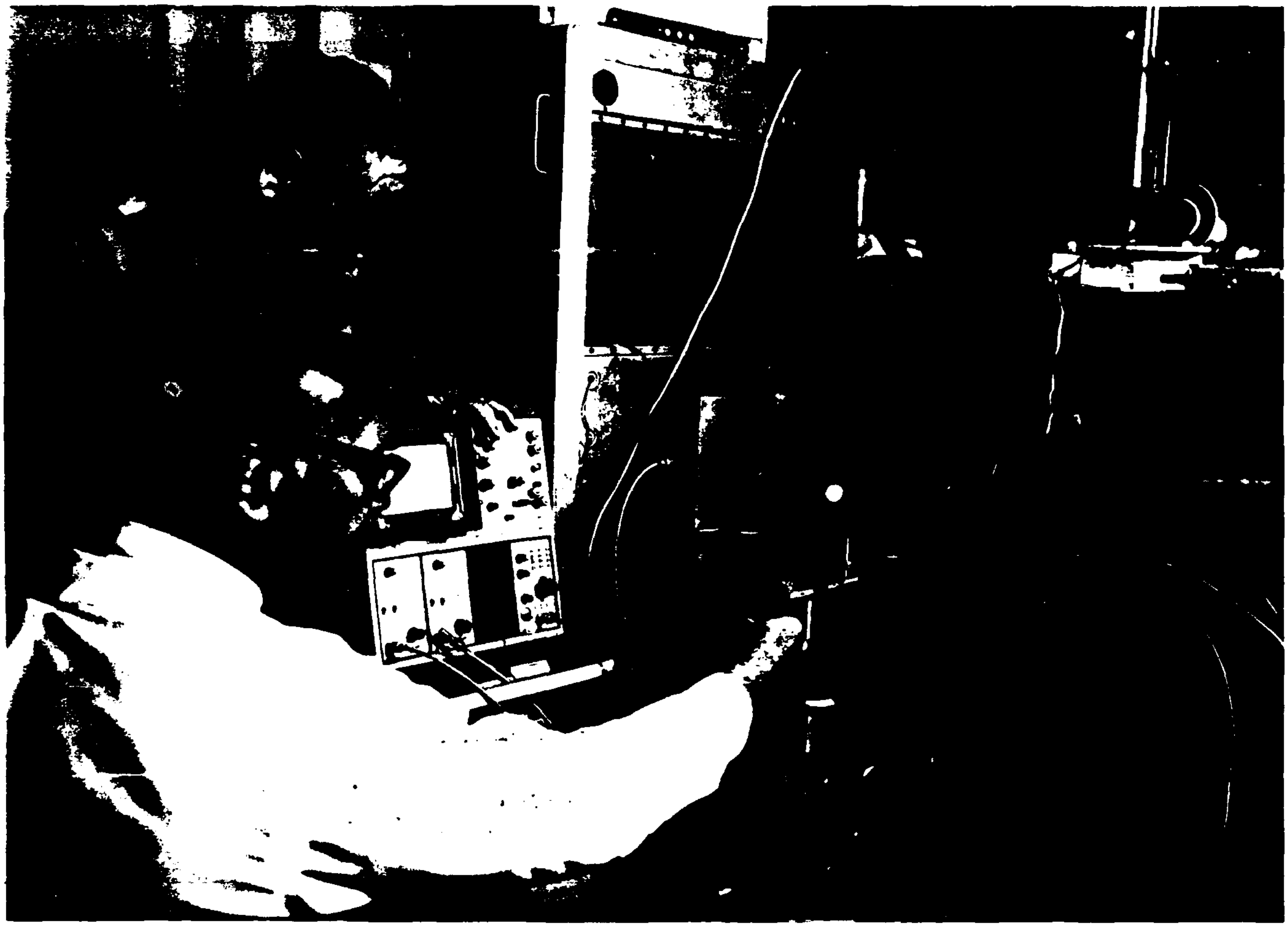


Figure 6

Mr. Fred Dyer (background) and Prof. Igor Alexeff making measurements on an Orbitron microwave maser.

Computational Physics Support

This activity, originally budgeted for $2,000 during the second year of this contract, was available to Dr. Robert Barker of AFOSR to support computational physics activities on his IBM AT computer. During this period of time, only a few hundred dollars was required by Dr. Barker, and the remainder was, with his permission, applied to support the undergraduate research fellowship program and/or to support graduate res rch assistant salaries. In May of 1987, Dr. Barker was able to obtain a more advanced computer for his computational physics research, and the IBM AT computer was returned to UTK where it became university property, having been purchased under a previous AFOSR contract. The computer was received intact and without damage in May, 1987 and was followed by the documentation and software originally purchased by Dr. Barker to support it. This AT computer is now set up and operating in the UTK Plasma Science Laborabory, has been used by our summer undergraduate research fellows during the summers of 1987 and 1988, and is routinely used by our graduate research assistants during the academic year.

1987 Summer Undergraduate Research Fellowship Program

The AFOSR Summer Undergraduate Research Fellowship program for 1987 was very successful. We had 9 undergraduate students participating in the program, all supported by the AFOSR and all of whom were U.S. citizens. They were supported under provisions of contract AFOSR 86-0100 (Roth), of which Dr. Robert J. Barker of AFOSR is technical program monitor.

We sent out announcements and application blanks for the program in late February 1987, with an April 1 deadline. We had 24 applicants, an

excellent group of engineering and physics students, most of whom had grade point averages above 3.5 on a scale of 4.0. Of these 24 applicants, two were women and 22 were men, and 21 of the 24 were from off campus, that is, not from UTK. Of the students selected for the program, there was one woman and eight men, and seven of the nine students were from off-campus. The affiliation of the off-campus students included Berea College, Kentucky; University of Virginia, Charlottesville; the Milwaukee School of Engineering, Milwaukee, Wisconsin; Virginia Tech, Blacksburg, VA; The State University of New York at Utica, NY; Vanderbilt University, Nashville, TN, and the North Carolina State University (NCSU) at Rayleigh, NC.

The students arrived on campus and started their summer activities on Monday, June 15, 1987. During the first two weeks of the program, Prof. Roth gave a series of lectures to orient the students to the field of plasma science, to laboratory research, and to the AFOSR research program at the UTK Plasma Science Laboratory. During the third and fourth weeks of the program, a series of equipment tutorials were given by the senior graduate research assistants to the summer students. These equipment tutorials were hands-on demonstrations of how to use some of the more sophisticated diagnostic, data handling, and electronic test instruments in the Plasma Science Laboratory. The summer students took advantage of the opportunity to use our equipment and were all very anxious to obtain hands-on experience in the plasma lab. Their comments on the program evaluation sheets, indicated that this opportunity for hands-on use of equipment was one of the most valuable aspects of their summer experience.

During the period from the first of July to the end of the program on August 21st, a series of lectures by senior faculty of the UTK Electrical and Computer Engineering Department were scheduled to introduce these summer students to graduate study and research in various areas of electrical engineering. Other activities of the summer students included a guided tour of the Fusion Energy Division and its activities at the Oak Ridge National Laboratory; a Saturday rafting trip on the Ocoee River; and separate weekend parties at the homes of Prof. Roth and Alexeff during the month of July. During the last two days of this program, on August 20 and 21st, the undergraduate fellows gave half hour oral presentations describing their work.

The AFOSR Undergraduate Summer Fellows were asked to spend 20% of their time on routine housekeeping activities to improve the work environment of the UTK Plasma Science Laboratory, and 80% of their time on a single research project that would be their responsibility. All of the summer undergraduate research fellows turned in a satisfactorily completed and documented research report. These topics included a report on Microwave Absorbtion Resonance Spectroscopy (MARS) by Mr. Jeff Henderson; a report on The Generation, Amplification and Secondary RF from the Orbitron Maser, by Mr. Greg Hisel; a Study of the Secondary Effects and Possible Amplification of the Orbitron Maser, by Miss Ann Kratz; a report on a X-Band Microwave Interferometer, by Mr. James W. McGuane; a report on the Interpretation and Analysis of Data for the Modified Penning Discharge, by Mr. David K. Miko; a report on Further Research Into Microwave Absorbtion Resonance Spectroscopy, by Mr. Christopher S. Saunders; a study of Solutions

to Quartic Equations, by Mr. Charles Smaw; a report on A Solid State Switching Circuit for Generating an RF Sawtooth Current for Collisional Magnetic Pumping Applications, by Mr. Kenneth E. Swayne; and finally, a report on the Construction, Operation, and Output of an Orbitron Maser with Multiple Cathodes and a Hot Filament by Mr. Derek L. Tattersall.

Accomplishments of The Third Year, March 15, 1988 to May 14, 1989

This section will discuss progress made from the beginning of the third year of the contract on March 15, 1988, to the final conclusion of research supported by this contract on May 14, 1989. A two-month extension was granted by AFOSR from March 15, 1989 to May 14, 1989 to accommodate the changed AFOSR policy now requiring that our new contracts start at the beginning of a month, and also to allow Professor Igor Alexeff an orderly transition from the contract on which we are now reporting, to his new AFOSR contract on plasma cloaking. Professor Roth's research covered by this report extends only to April 1, 1989, at which time a subsequent contract, AFOSR-89-0319, took effect. Professor Alexeff's research program covered by this report extended to May 1, 1989, at which time a new AFOSR contract took over. Unless noted otherwise, the activities discussed below were within budget and on schedule during this contract period.

Collisional Magnetic Pumping Research

This third year of our research program marked the completion, under Air Force sponsorship, of our research program on collisional magnetic pumping. Dr. Mounir Laroussi, our senior AFOSR graduate research assistant, completed his Ph.D. thesis, and obtained his degree at the June, 1988 graduation. Dr. Laroussi remained as a post-doctoral associate until July 15, 1988, at which time he returned to do teaching and research at the Technical University in Sfax in his native Tunisia. An abstract and the title pages of his Ph.D. thesis are included in Appendix H. Three major chapters of this thesis were extracted and prepared for archival publication. These include the journal articles listed in Appendix D, as numbers 13 - 15. Full length versions of these papers are in appendix E, starting on pages E-57, E-65, and E-99. The first two of these have already been published in the Physics of Fluids. A final report on the experimental part of Dr. Laroussi's thesis was presented at the June, 1988 IEEE International Conference on Plasma Science. An abstract of this presentation is listed in Appendix G, on page G-19.

Prior to Dr. Laroussi's departure, and starting approximately in January in 1988, a second graduate research assistant, Mr. Min Wu, prepared to carry on Dr. Laroussi's research program in collisional magnetic pumping by applying this heating method to a cylindrical plasma located in a mirror magnetic field (Dr. Laroussi's data were all taken on a cylindrical plasma in an axially uniform magnetic field). By the summer of 1989, Mr. Wu completed his experimental master's thesis, involving the measurement of plasma heating by collisional magnetic pumping, which was observed in this

Penning discharge plasma in a magnetic mirror field. The experimental work of Mr. Wu was reported at the APS meeting in 1988 in the abstract that is included in this publication in Appendix G, on page G-21, and further results were reported by Mr. Wu at the 1989 IEEE International Conference on Plasma Science in Buffalo, New York. This IEEE paper is included in Appendix G, an abstract of which is on page G-26.

The three year program of research on collisional magnetic pumping for the AFOSR has shown both analytically and computationaly that first order plasma heating should be possible, if the magnetic purturbation is sawtooth in time, and with a fast drop at the end of the sawtooth which is short compared to the collision time in the plasma. The experimental investigations of Dr. Laroussi and Mr. Wu, in two different magnetic field configurations, have both demonstrated measurable plasma heating by amounts that are above the intrinsic errors of the experimental procedures used, and which would be difficult to explain by other plasma heating mechanisms. The observation of measurable plasma heating is not consistent with second order heating by collisional magnetic pumping, since such heating would be well below the range of detectability of our experimental methods. Dr. Laroussi has shown agreement between analytical theory, the computational physics results, and the functional dependences on the experimental parameters that have been observed experimentally. The amount of plasma heating experimentally observed is somewhat larger, by a factor of 3 to 5, than predicted theoretically. This increased heating can be understood as a consequence of longer particle containment times in the interior of the plasma than on the outside. On

Figure 7is a photograph of the AFOSR apparatus on which Dr. Laroussi did his Ph.D. thesis on collisional magnetic pumping.

Plasma Turbulence Research

During this final year, the research program on plasma turbulence, which was supported in part by AFOSR, was also wound up. During this time, Mr. Scott A. Stafford completed research for a master's degree in electrical engineering with the title "Investigation of the Nonlinear Behavior of a Weakly Ionized Plasma". Poster papers on this research were presented at the 1988 APS Plasma Physics Division Meeting, and also at the 1989 IEEE International Conference on Plasma Science, in Buffalo, New York. Support of Mr. Stafford's thesis work on plasma turbulence during the period following January, 1988 was shared by the Office of Naval Research, and the Air Force Office of Scientific Research.

In this thesis research we had the benefit of advice from Prof. Mark Kot (whose time was not charged to the contract) of the UTK Department of Mathematics, whose field of research is nonlinear dynamics. In his thesis research, Mr. Stafford used the methods of nonlinear dynamics to study the characteristics of the electrostatic turbulence in a magnetized, steady-state, partially ionized plasma. Electrostatic potential fluctuation data were obtained by a capacitive probe. These signals were captured, digitized, and recorded with a LeCroy transient recorder system, interfaced to an IBM AT personal computer. A commercially available software program was used to calculate Fourier spectra, reconstruct and plot phase spectra in three dimensions, take Poincare sections, compute correlation dimensions, obtain Lyapunov exponents, and perform other manipulations of the time series of

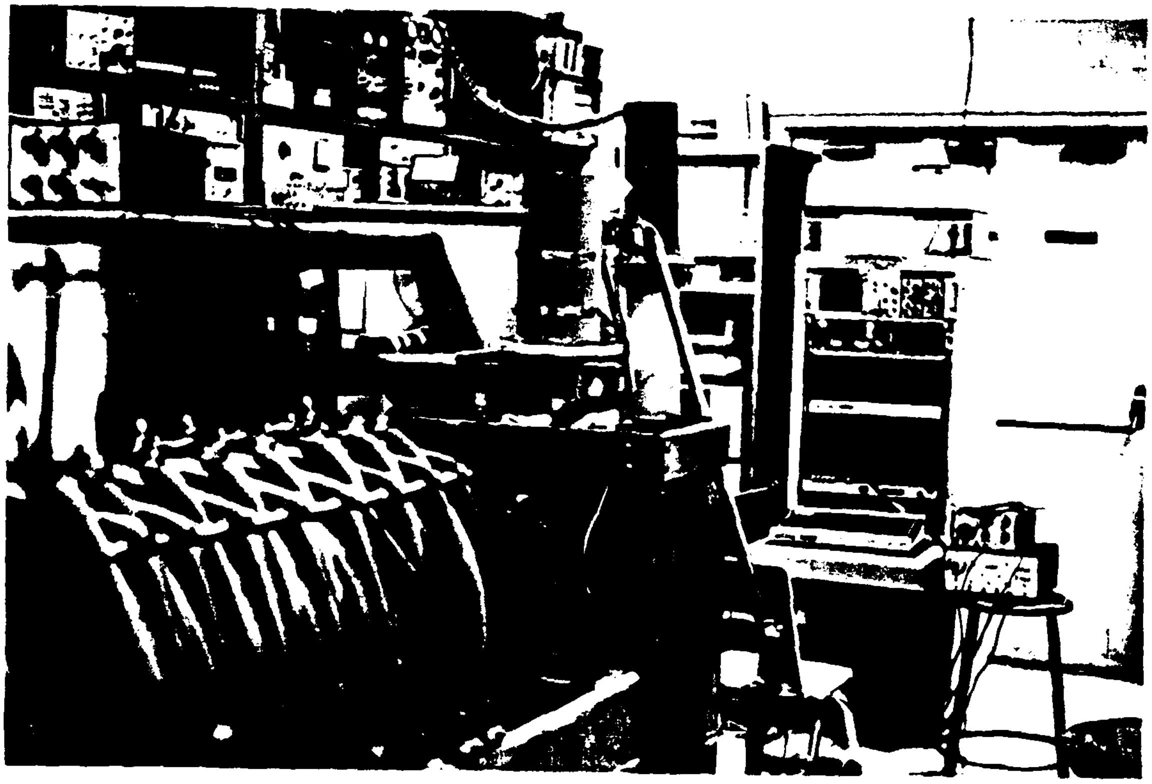


Figure 7

electrostatic potential fluctuations obtained from the plasma. Mr. Stafford looked for evidence of low dimensional chaos, and investigated trends which related the state of the turbulence to such plasma parameters as the anode voltage, background gas pressure, and magnetic induction. These three variables were found to have a significant effect on the state of turbulence and on the nonlinear dynamics of the plasma. These investigations of Mr. Stafford's may very well be the first time that the reconstructed phase spectrum and other nonlinear-dynamical parameters have been measured as a function of these plasma parameters. Most previous investigations were concerned with a single set of operating conditions.

Plasma Cloaking Research

During the final 9 months of this contract period, starting in early May, 1988, Prof. J. R. Roth and Prof. Igor Alexeff became involved in the AFOSR program on plasma cloaking research, a topic not originally contemplated in the original three-year research program. Our involvement in this area came quite naturally, because the microwave network analyzers which we purchased with AFOSR URIP grant money allow us to perform many kinds of investigations relating to the absorption and reflection of electromagnetic radiation from plasmas which are not possible without these instruments.

A common theme of research programs in the University of Tennessee's Plasma Science Laboratory is the study of electric field dominated, steady state plasmas. Some recent results are relevant to the absorption of electromagnetic radiation by magnetized plasmas and provide corroboration of the basic premise of the plasma cloaking concept: that significant

attenuation at microwave frequencies may be possible by using plasma absorbers.

The basic idea of using a plasma to interfere with or absorb probing radar signals was first mentioned to Prof. Roth by Dr. Robert J. Barker of AFOSR/NP approximately 2 1/2 years ago. The idea of plasma cloaking surfaced again at a meeting of the AFOSR/AFGL Scientific Advisory Panel on Artificial Atmospheric Plasmas, which was held at the Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts, on May 3 and 4, 1988. In this brainstorming session, Dr. Barker described his basic concept of surrounding a potential radar target with plasma, to interfere with radar observations. During that meeting, Prof. Roth presented some data from the UTK Plasma Science Laboratory, which indicated that magnetized plasmas could absorb several tens of dB of incoming microwave energy in the extraordinary mode, using relatively low density plasmas (no more than 10^8 to 10^9 per cubic centimeter) and at frequencies ranging from 2 to 12 gigahertz, which spans the range used by many military radar systems.

Prof. Roth's modification of Dr. Barker's concept, presented at that meeting, was to assure absorption of incoming electromagnetic radiation by using a <u>magnetized</u> plasma, for which the electron cyclotron frequency associated with a spatially varying magnetic field would span the frequency range of any probing radar signals. The plasma cloaking concept that Prof Roth suggested was to put a superconducting coil, which would generate a dipole magnetic field, in a target such as an aircraft or a space satellite. The dipolar magnetic field could be supplied with a weak plasma to form a "magnetosphere" surrounding the target. In this concept, probing radar

signals of a wide range of frequencies would enter this artificial magnetosphere surrounding the target, and be absorbed when they reached a magnetic induction corresponding to the electron cyclotron frequency. This concept poses a number of questions which need to be addressed, including how you would generate such an artificial magnetosphere about a radar target (this is likely to be easy at orbital altitudes, since a dipolar field will probably fill up with plasma much as the earth's magnetosphere does, from its surroundings; the situation in the atmosphere is not so clear; perhaps flashboards or glow discharges might be used) but this aspect is not a part of our ongoing research program.

The findings of the AFGL Scientific Advisory Panel indicated that the plasma cloaking concept which Prof. Roth presented, based on absorption by magnetized plasmas, was very interesting and should be vigorously pursued by the Air Force.

The Appleton equation describes the interaction of electromagnetic radiation with a magnetized plasma. It predicts that the complex dielectric constant in the extraordinary mode, for which the electric field is perpendicular to the magnetic field, is given by

$$\mu_{ex} = 1 - \cfrac{\omega_p^2/\omega^2}{1 - j\dfrac{\nu}{\omega} - \cfrac{\omega_b^2/\omega^2}{1 - \omega_p^2/\omega^2 - j\,\nu/\omega}}$$

$$= |\mu - j X|^2$$

$$\alpha = \frac{\omega}{c} X \qquad \beta = \frac{\omega}{c} \mu$$

and

ω_p = plasma frequency,

ω_b = gyro frequency,

ω = wave frequency, and

v = collision frequency

The parameters α and β are the wave propagation constants. Consideration of the Appleton equation indicates that significant absorption (several ten's of dB) should occur in the vicinity of the electron cyclotron frequency for plasmas of only moderate number densities (10^8 and 10^9 electrons per cubic centimeter). For magnetic inductions between about 0.010 and 0.42 tesla (typical of our experiment in the UTK Plasma Science Laboratory) the electron cyclotron frequency ranges from 0.28 gigahertz to 11.8 gigahertz, the range of interest for many military radar systems.

The Appleton equation is based on cold plasma theory, for which the velocity distribution function of the ions and electrons are both ignored. Hot plasma effects, due to finite temperature of the ions and/or electrons, and the effect of instabilities, particularly scattering by fluctuating electric fields resulting from plasma turbulence, are likely to modify the predictions of the Appleton equation. It can be anticipated that the direction of such influence will be to increase the absorption of incident electromagnetic radiation in both the ordinary and extraordinary modes of propagation, but this point needs to be confirmed analytically where possible, and by experimental measurement in any case.

In order to support our optimism for the success of plasma cloaking using a magnetized plasma, some recent experimental data are summarized below, which were generated in the UTK Plasma Laboratory, on the absorption of 9.75 gigahertz radiation at the electron cyclotron frequency. We also summarize some very recent results on the absorption of microwave radiation in the frequency band from 2 to 10 gigahertz for the extraordinary mode of microwave radiation propagating in a modified Penning discharge. In this discharge, the magnetic induction varied in the plasma volume by a factor of at least 1.6. This latter work was reported in a poster paper which is included in Appendix G, page G-22.

On Figure 8 is a schematic of the classical Penning discharge, with a uniform axial magnetic field, which produced the data which I will discuss below. The Penning discharge is operated in the steady state, and at magnetic inductions that vary between 0.10 tesla and 0.42 tesla. Pertinent features of this dischrge are that it is electric field dominated, with strong axial and radial electric fields, sometimes exceeding several hundred volts per centimeter, and it has high levels of plasma turbulence, maintained by the energy input from the applied electric fields. The ions and electrons are heated by E/B rotation, which gives rise to an ion population that is hotter than the electron population. This classical Penning discharge was used in our collisional magnetic pumping experiment.

On Figures 9 and 10 are shown some characteristic data taken along the axis of the discharge. The electron number density was typically 10^9 per cubic centimeter, and the electron temperature was about 10 eV. This classical Penning discharge was instrumented with a variety of diagnostics, including

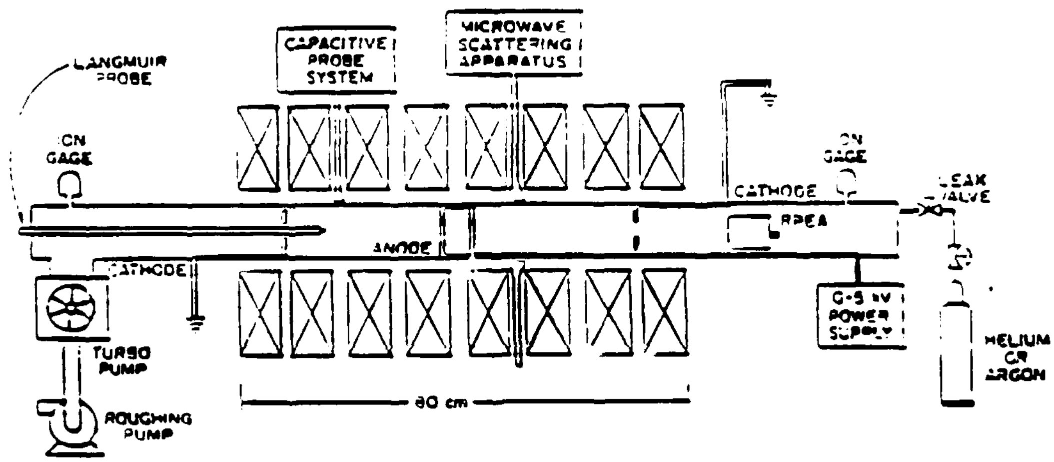


Figure 8 Schematic of the classical Penning discharge with uniform axial magnetic field in the plasma volume.

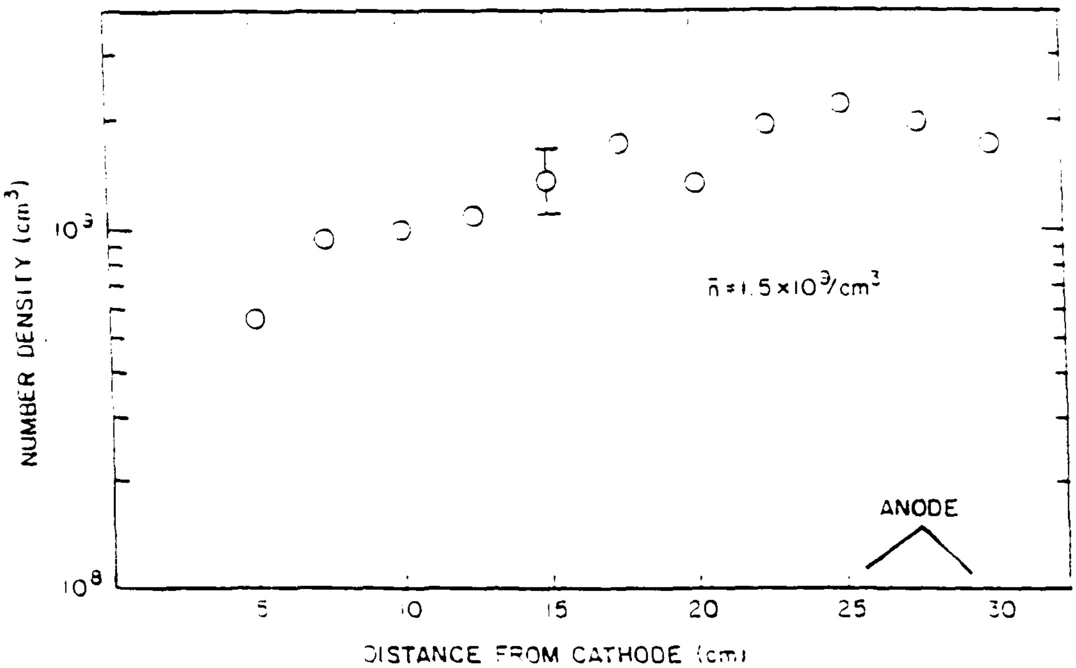


Figure 9 **Axial profile of the number density at V_A = 1.5 kV, I_A = 40 mA, P = 100 μ Torr, B = 0.255 T.**

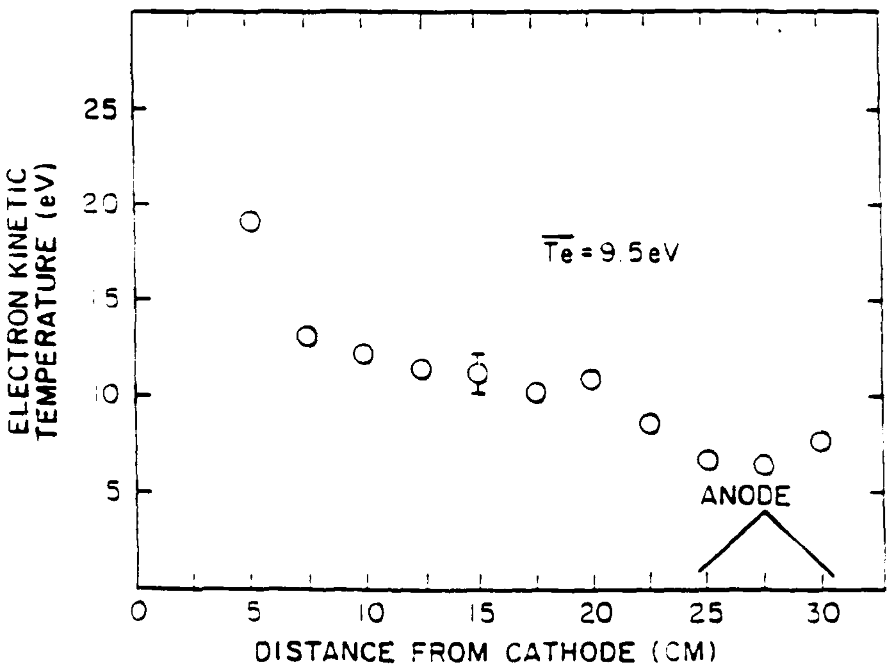


Figure 10 **Axial profile of the electron kinetic temperature at V_A = 1.5 kV, I_A = 40 mA, P = 100 μ Torr, B = 0.255 T.**

the axial Langmuir probe that produced the data on Figures 9 and 10. Also included was the experimental setup shown on Figure 11, in which a transmitting horn and a receiving horn were put on either side of the cylindrical plasma, and connected to an HP 8510 microwave network analyzer. The microwave network analyzer is the most sophisticated instrument at the UTK Plasma Science Laboratory, and was purchased with funds provided by the Air Force under the University Research Instrumentation Program (URIP). This network analyzer makes it possible for us to irradiate the plasma with a microwave signal of variable frequency over the range from 0.2 to 18 gigahertz. After passing through the plasma, the signal is picked up by the receiving horn and analyzed by the network analyzer.

The purpose of the instrumentation shown in Figure 11 was to implement a new diagnostic, intended to measure experimentally the effective electron collision frequency in the plasma. The dielectric constant for the extraordinary mode in a plasma is given by the Appleton equation, below Figure 11. This equation contains the electron cyclotron frequency, the electron plasma frequency, and the collision frequency. It can be shown that the full width of the absorption peak, at half-maximum amplitude at the electron cyclotron frequency, is related to the effective electron collision frequency appearing in the Appleton equation. Thus, a measurement of the resonant absorption peak at the electron cyclotron frequency with the microwave network analyzer will allow a measurement of the effective collision frequency.

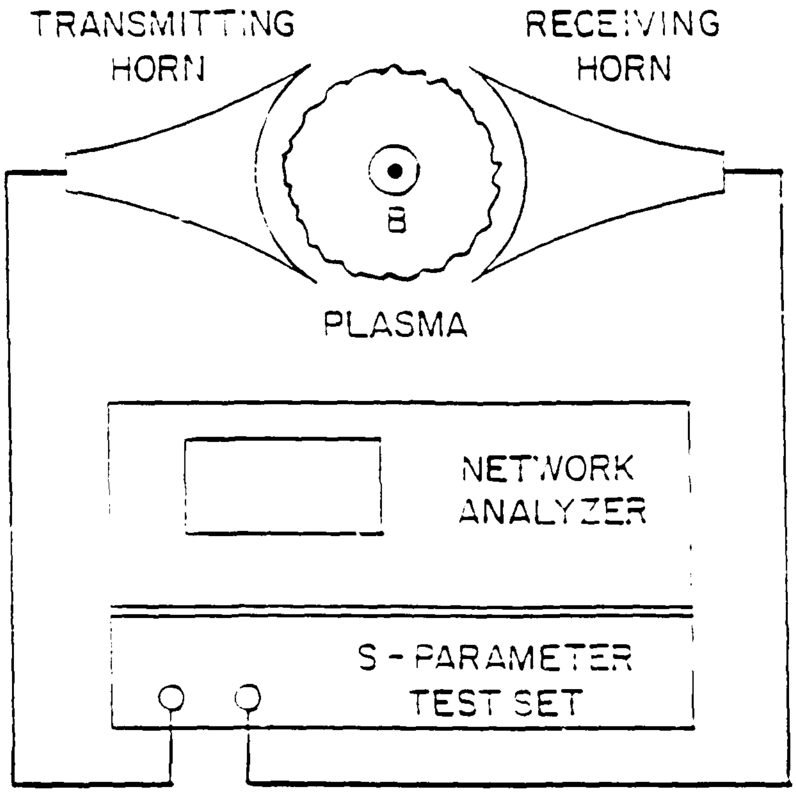


Figure 11 **Experimental setup for the measurement of the effective collision frequency.**

$$\varepsilon(\omega) = \mu_{ex}^{2} = 1 - \frac{\dfrac{\omega_p^2}{\omega^2}}{1 - j\dfrac{v_c}{\omega} - \dfrac{\omega_{cy}^2/\omega^2}{1 - \dfrac{\omega_p^2}{\omega^2} - j\dfrac{v_c}{\omega}}}$$

Some characteristic data are shown on Figure 12. Here, the electron cyclotron frequency was approximately 9.75 gigahertz. At this frequency, the absorption of the power was about 36 dB. The full width at half maximum of this curve yields an effective electron collision frequency of 7.5 megahertz, more than a factor 30 higher than the binary electron-neutral collision frequency shown in the Table below Figure 12. The value of the effective collision frequency, and the fact that it is usually much higher that the binary collision frequency in this turbulent plasma, is of great theoretical interest. This type of measurement has not previously been reported in the literature, prior to our observing it with the equipment we purchased with Air Force support under the URIP program.

For the present discussion of plasma cloaking, the point of interest in Figure 12 is the very large attenuation achieved in the vicinity of the electron cyclotron frequency, 36 dB in Figure 12. This large attenuation was in no way unusual, and even higher attenuations were sometimes observed. The processes occuring in the plasma are relatively complicated, and are not fully described by the Appleton equation, which is based on the cold plasma approximation. The minor satellite peak in Figure 12 to the left (lower frequency) of the electron cyclotron frequency represents a hot plasma effect. The fact that only a single such peak is seen, on one side of the electron cyclotron frequency, strongly indicates a nonlinear interaction. The general magnitude of the observed attenuation is consistent with the predictions of the Appleton equation, however, since this equation predicts attenuations that are typically 10's of dB for plasmas such as those in this classical Penning discharge. The average plasma density was approximately 1.5×10^{9} particles

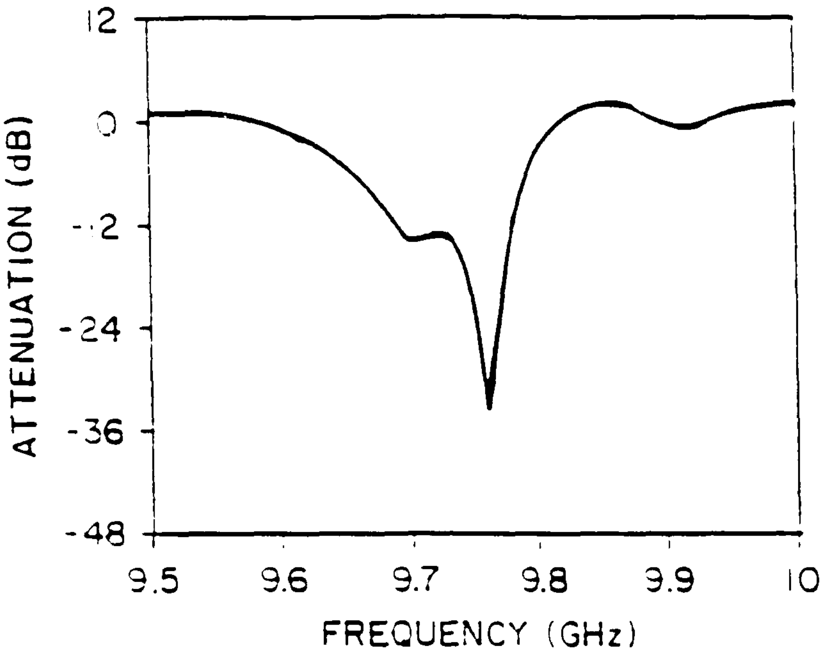


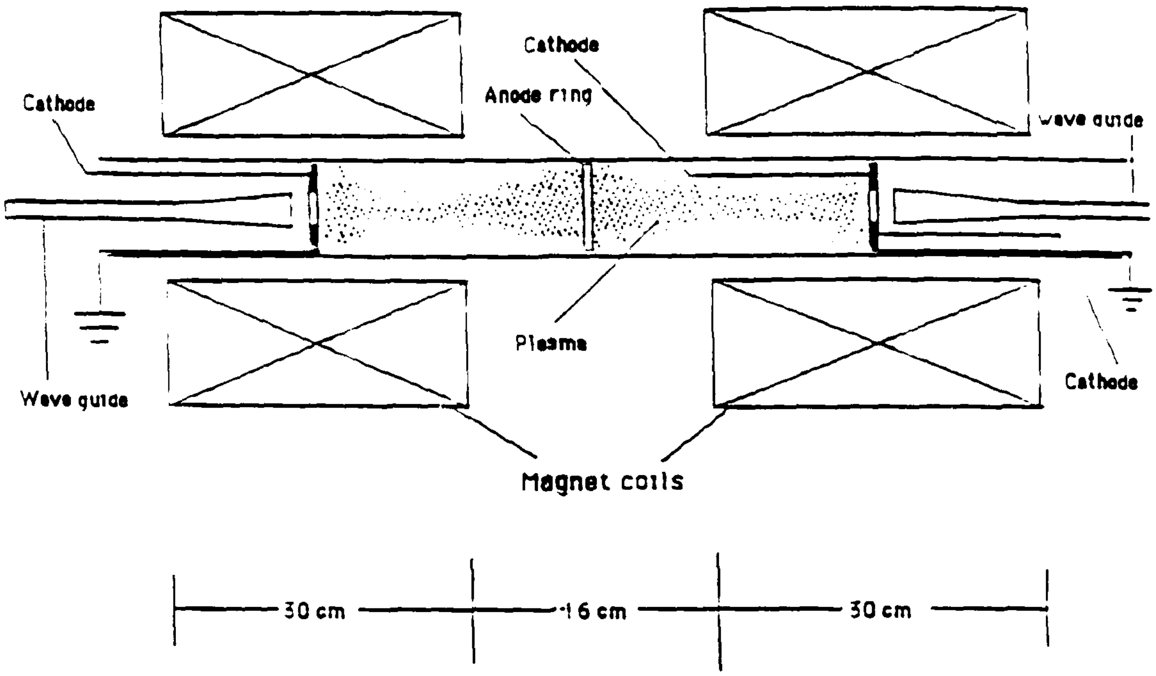
Figure 12 **Resonance absorption curve with an effective collision frequency of 7.5 MHz.**

Collision	Collision Frequency, Hz
Electron-Neutral	265 10^3
Ion-Neutral	[illegible]
Electron-Electron	[illegible] 10^3
Electron-Ion	950
Neutral-Neutral	137
Ion-Electron	0.5
Ion-Ion	0.177
Effective Collision Frequency (Fig E.18)	7.5 10^6

per cubic centimeter. The plasma diameter was typically 12 or 15 centimeters, thus making the columnar density of the plasma no more than about 2 x 10^{10} electrons per square centimeter. Thus, at the electron cyclotron frequency in a magnetized plasma, the electrons can very effectively absorb microwave power in the gigahertz range. Figure 12 is an example of absorption at 9.75 gigahertz; in the experiments on the classical Penning discharge absorption was observed from approximately 5 gigahertz up to about 15 gigahertz during the course of these experiments.

It appears that very large attenuations of microwave power are possible in rarefied plasmas and plasmas with relatively small columnar densities, provided only that they are in a magnetic field. The data referred to thus far and shown in Figure 12 were taken for the extraordinary mode, in which the electric field vector of the wave is perpendicular to the magnetic field. Similarly large absorptions are not necessarily to be expected in the ordinary mode, with E parallel to B.

Some more recent data have been taken, which were reported at the 1988 APS Plasma Physics Division meeting in a poster paper, an abstract of which in included as Appendix G, on page G-21. In this experiment, a classical Penning discharge, which was the Air Force apparatus in the UTK Plasma Science Laboratory, was converted into a modified Penning discharge with a magnetic mirror configuration having a ratio of maximum to minimum magnetic field of 1.6 to 1 along the axis. The geometry is shown schematically in Figure 13. The cathodes of the Penning discharge were located at the magnetic field maximum, and immediately behind each was located a microwave horn which was screened from the plasma by horizontal grid wires



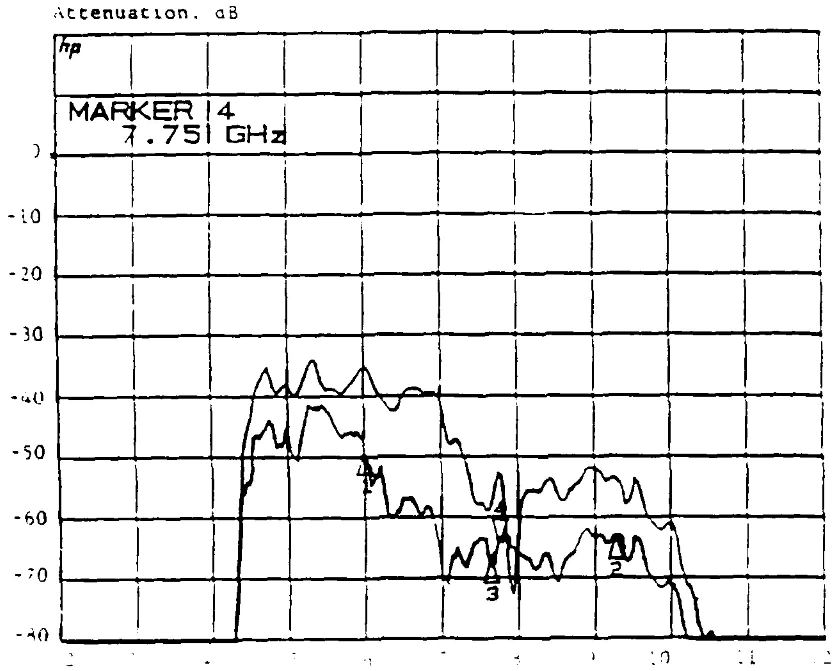
MODIFIED PENNING DISCHARGE
(TOP VIEW)

Figure 13

aligned parallel to the electric field of the microwave radiation. This allowed microwave radiation from approximately 4 to 10 gigahertz to propagate through this magnetized plasma in the extraordinary mode, with a magnetic field variation of at least 1.6 to 1 along the path of microwave propagation. The microwave horns were hooked up to our Hewlett Packard Model 8510 microwave network analyzer, which was swept over frequencies from 2 to 12 gigahertz. It was expected that attempting to propagate the microwave signal through a plasma embedded in a variable magnetic field would greatly broaden the bandwidth over which electron cyclotron resonance absorption occurred. This expectation was observed.

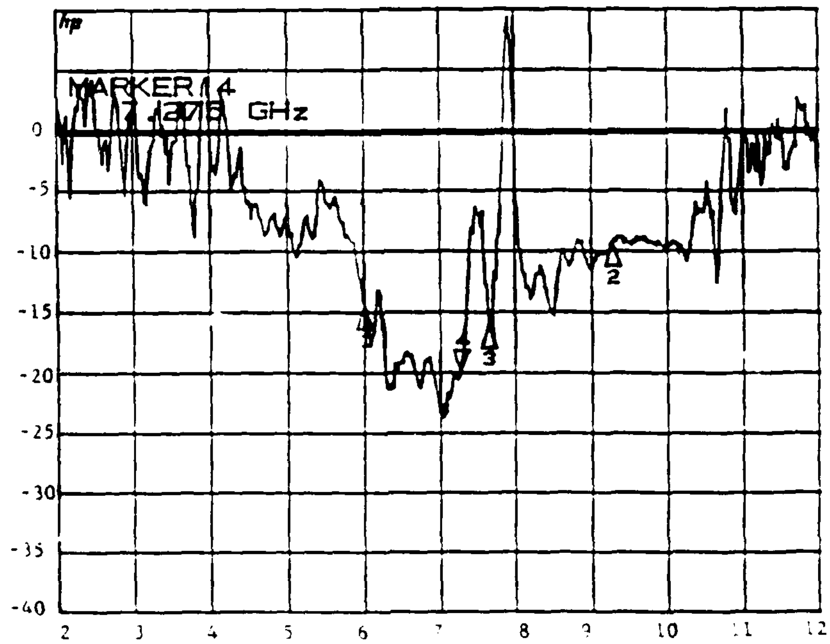
On Figure 14 is shown the absolute attenuation of the microwave signal from approximately 4.3 GHz to 10.5 GHz. Beyond these frequency limits, the microwave waveguide and other circuit components cut off. The upper curve is the attenuation of the system with the plasma off. The lower curve shows the transmission through the system with the plasma on. In this case, there is up to approximately 20 db of attenuation at frequencies which have an ion cyclotron resonance in the plasma volume.

The normalized attenuation is shown on Figure 15, which shows the attenuation curve normalized to the signal received without the plasma. Here the attenuation is at least 5 dB over the entire range, and a maximum of more than 20 dB. Markers No. 2 and 1 on this plot indicate, respectively, the electron cyclotron resonance frequencies corresponding to the maximum and minimum of the magnetic induction in the plasma volume. It is interesting to note that significant attentuation occurs even at frequencies for which there is no electron cyclotron resonance in the plasma containment volume. Figure 16



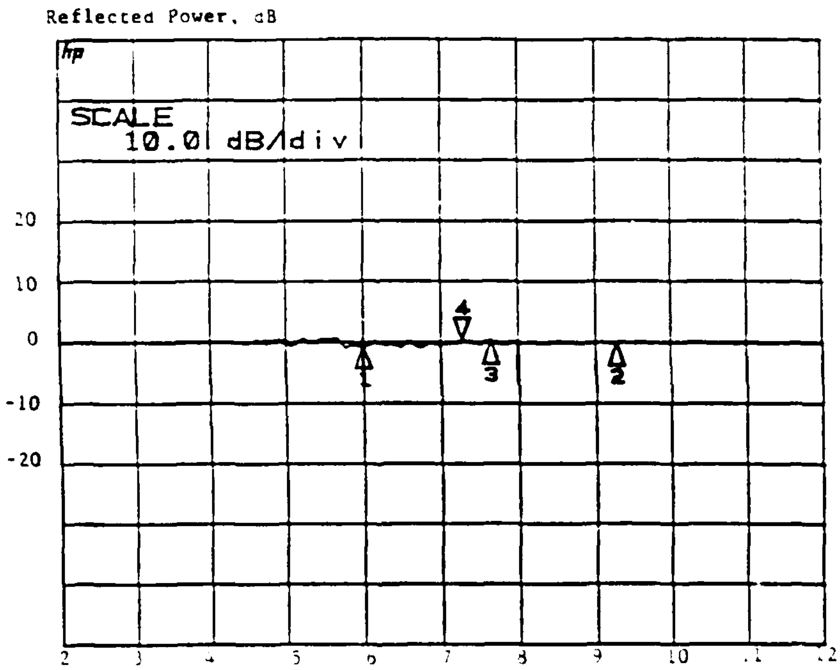
Frequency, GHz
Plasma Attenuation. Upper curve: plasma off
lower curve: plasma on

Figure 14



Frequency, GHz
Normalized Plasma Attenuation

Figure 15



Frequency, GHz

Normalized Plasma Reflection

Figure 16

shows the normalized reflection of microwave signal from the plasma. In all cases, including this one, the reflected signal was within the noise limits of the system, and no more than one or two dB. These data are a very encouraging indication that magnetized plasmas can not only absorb, but also not reflect any significant signal when the incoming radiation is in the extraordinary mode, and in electron cyclotron resonance. Finally, Figure 17 shows the attentuation in dB as a function of the Penning anode current, which is proportional to the electron number density in the plasma. This shows a monotone increase of attenuation with electron number density, a dependence which is to be expected on the basis of the Appleton equation and elementary physical considerations.

During the final few months before April 1, 1989, cloaking research was continued in anticipation of the current two-year research contract on plasma cloaking. In this research program, the intent was to propagate microwave radiation at the electron cyclotron frequency across the diameter of a cylindrical plasma, using a slab geometry. A special set of microwave horns were to designed to propagate radiation in the ordinary and extraordinary mode in a thin slab which included the axis of the cylindrical plasma, but not the curved regions near the top and bottom of the plasma column. Some results of the antenna design and a few initial plasma measurements were presented at the 1989 IEEE International Conference on Plasma Science in Buffalo, New York in May. An abstract of this paper on plasma cloaking is included in Appendix G, on page G-25.

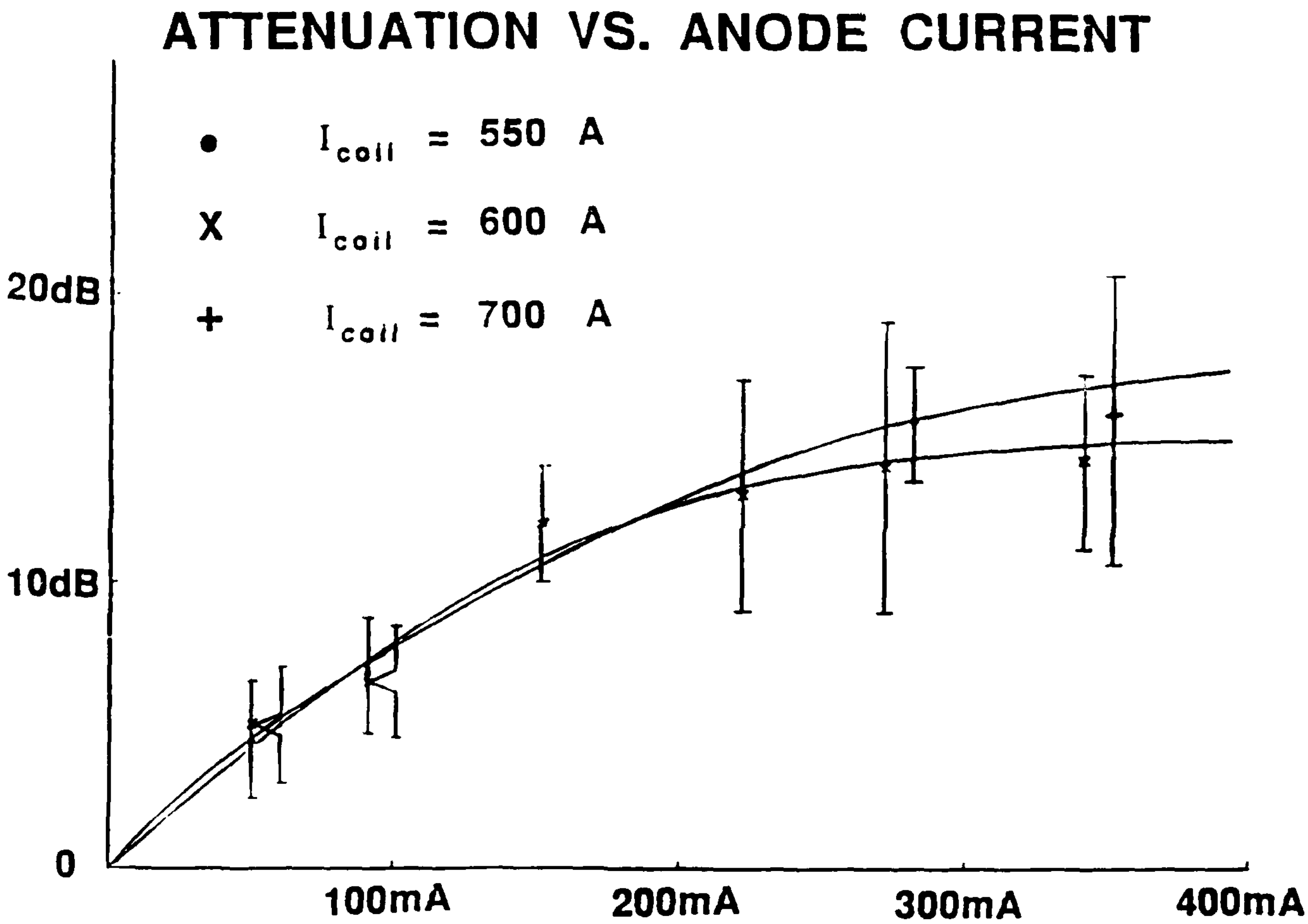

ATTENUATION VS. ANODE CURRENT
• I_{coil} = 550 A
X I_{coil} = 600 A
+ I_{coil} = 700 A
20dB
10dB
0
100mA
200mA
300mA
400mA

Figure 17

Orbitron Research

The final year of this three year research program was a year of consolidation of gains made in understanding and developing the process of millimeter and submillimeter microwave emission from Orbitrons, and also of laying the foundation for new directions, involving a plasma cloaking concept which originated with Prof. Igor Alexeff and uses the Doppler shifting of radar signals by dense, expanding plasmas. The Orbitron research, all of which was under the responsibility of Prof. Igor Alexeff, was continued until May, 1989, under a two-month extension of our three-year contract. Work performed under this extension was covered by the originally budgeted amount for twelve months, the program having been stretched out to bridge the gap between the three-year program discussed in this proposal, and the separate subsequent contracts of Profs. Roth and Alexeff.

The consolidation of the Orbitron-related work can best be seen in Appendix D, which lists the archival publications on the Orbitron which were written up during that time. These included an invited paper at the IEEE Southeastcon '88 IEEE meeting, given by Prof. Igor Alexeff, and a second paper on a prototype commercial Orbitron maser for millimeter radar by Prof. Alexeff, Mark Rader, Fred Dyer, and collaborators from industry, which was presented at the 13th conference on Infrared and Millimeter Waves. Another paper at that same meeting was presented by Prof. Alexeff et al. on a pulsed and steady-state multi-anode Orbitron maser. Some of the poster and oral conference presentations on the Orbitron during this period are listed in Appendix F, as items 20, 23, 24, 27, and 28. At the 1988 IEEE International Conference on Plasma Science in Seattle WA, Prof. Alexeff and his colleagues

presented papers on the magnetic output control and external frequency control of the Orbitron maser. At the American Physical Society's Plasma Physics Division Meeting in November, 1988, an Orbitron-related paper on magnetic output control and self damping of the Orbitron maser, and a second paper on steady-state operation of the gas-filled Orbitron maser, were both presented. In the final stages of the AFOSR-supported Orbitron work at UTK, papers were prepared for the 1989 IEEE International Conference on Plasma Science in Buffalo, New York on the steady-state, gas-filled Orbitron maser. AFOSR-supported work on the Orbitron maser ended in May, 1989.

1988 Summer Undergraduate Research Fellowship Program

The AFOSR Summer Undergraduate Research Fellowship program for 1988 was very successful, and much learning took place. We had 8 undergraduate students participating in the program, all supported by the AFOSR and all of whom were U.S. citizens. They were supported under provisions of contract AFOSR 86-0100 (Roth), of which Dr. Robert J. Barker of AFOSR is technical program monitor. This was the fourth year of the program here at UTK.

This year, we sent out announcements and application blanks for the program in early February 1988, with an April 1 deadline. We had 15 applicants, an excellent group of engineering and physics students, most of whom had grade point averages above 3.5 on a scale of 4.0. Of these 15 applicants, one was a woman and 14 were men, and 12 of the 15 were from off campus, that is, not from UTK. Of the students selected for the program, there was one woman and 7 men, and five of the eight students were from off-

campus. The affiliations of the off-campus students included Auburn University, AL; Bethany College, Bethany, WV; Brown University, Providence, RI; Indiana University, Indiana, PA; and the College of Charleston, Charleston, SC.

The students arrived on campus and started their summer activities on Monday, June 13, 1988. Orientation material describing the program and the UTK Plasma Science Laboratory, was given to them on the first day. During the first two weeks of the program, Prof. Roth gave a series of lectures to orient the students to the field of plasma science, to laboratory research, and to the AFOSR research program at the UTK Plasma Science Laboratory. During the third and fourth weeks of the program, a series of equipment tutorials were given by the senior graduate research assistants to the summer students. These equipment tutorials were hands-on demonstrations of how to use some of the more sophisticated diagnostic, data handling, and electronic test instruments in the Plasma Science Laboratory. The summer students took advantage of the opportunity to use our equipment and were anxious to obtain hands-on experience in the plasma lab. Their comments on the program evaluation sheets, indicated that this opportunity for hands-on use of equipment was one of the most valuable aspects of their summer experience.

During the period from the first of July to the end of the program on August 19th, a series of lectures by senior faculty of the UTK Electrical and Computer Engineering Department were scheduled to introduce these summer students to graduate study and research in various areas of electrical engineering. Other activities of the summer students included a guided tour of the Fusion Energy Division and the laser laboratory at the Oak Ridge

National Laboratory; a Saturday tubing trip in the Smokies; and a final banquet at the UTK Faculty Club on August 18. During the last two days of this program, on August 18 and 19th, the undergraduate Fellows gave twenty minute oral presentations describing their work, which were accompanied by writeups.

The AFOSR Undergraduate Summer Fellows were asked to spend 20% of their time on routine housekeeping activities to improve the work environment of the UTK Plasma Science Laboratory, and 80% of their time on a single research project that would be their responsibility. All of the summer undergraduate research fellows turned in a satisfactorily completed and documented research report. These topics included a report on the "Development of a (Langmuir probe) Plasma Data Acquisition System", A joint project of Mr. Tom Karnowski, Mr. John J. Teddington, and Ms. Audrey Van Blommesteyn; "The Gas-Filled Steady-State Orbitron Maser", by Mr. James J. Carroll; "The Double Grid Barkhausen-Kurz Oscillator", by Mr. Andrew S. Getter; a "Microwave Scattering System", by Mr. Joseph T. Mang; "Mode Coupling in a Two Channel Turbulent Plasma", by Mr. Osama Taha; and "Orbitron Emissions Produced by Multiple Anode Wires", by Mr. Carl H. Rourk, III. The full text of these papers may be found at the end of this report.

This was the fourth year of the UTK-AFOSR Summer Undergraduate Research Fellowship Program, and I feel that by now it has evolved to the point where we can with a great deal of confidence recruit excellent students from technical schools and colleges all over the Eastern United States, and keep them productively occupied with interesting and meaningful projects during their summer program. The emphasis in future years should, I think,

be in terms of maintaining the high ground we have now reached in this program and keeping it functioning with the current level of success, rather than making further adjustments or changes.

Miscellaneous Technical Accomplishments

The above sections of this chapter give an account of the research program supported by the AFOSR over the 3-year period covered by this report. The topics discussed in those sections are the "mainline" research topics on which probably 95% of our time and energy were focussed, and which we originally proposed to do before undertaking the work, except for plasma cloaking. Because we are a basic research laboratory devoted to exploratory research, a few other topics came up which were done with time and resources made possible by AFOSR support, even though they represented topics which were not originally proposed for support.

In the early Spring of 1987, Prof. Roth became interested in the industrial applications of plasma, and saw a way to apply some of the AFOSR-supported research results to industrial plasmas. Accordingly, Prof. Roth prepared a paper on the theory of plasma ion implantation, which he presented at the IEEE conference in Washington, DC, in 1987. An abstract of this paper is included on page G-13 of Appendix G. This paper elicited the largest number of reprint requests of any of the AFOSR-supported papers which are included in Appendix G. Also, one of our diagnostic papers, by John Crowley, his Master's thesis and one of our diagnostic development papers, was presented at the 1986 APS Plasma conference, an abstract of which is included on page G-7 of Appendix G.

Other technical accomplishments which were performed by the Principal Investigators during this period of AFOSR support include the publication by Prof. J. R. Roth of a textbook "Introduction To Fusion Energy" by InPrint Inc., in Charlottesville, VA in 1986; the editing by Prof. Igor Alexeff of a book "High Power Microwave Sources" by Artech House in Norwood Mass., and a paper accepted for publication in the Transactions on Plasma Science entitled "A Visible Plasma" by Prof. Alexeff, with the collaboration of Fred Dyer and M. Rader.

Other technical accomplishments included a collaboration between Profs. Alexeff and Roth on "A Simple MHD Model for Confinement Time Scaling in Tokamaks" which was presented at the IEEE International Conference on Plasma Science in 1986, another collaboration between Profs. Alexeff and Roth "An Improved MHD Model of The Earth's Magnetic Field", also presented at the IEEE meeting of 1986. These two collaborative papers are listed in Appendix G on pages G-1 and G-3, respectively.

POTENTIAL UTILITY OF RESEARCH TO THE AIR FORCE

The basic research on steady state electric field dominated plasmas described in this report has potential relevance to several areas of Air Force concern. These include the production of steady-state, high power microwave emission at sub-millimeter wavelengths; the production rf emissions suitable for military communications; the heating of plasmas by collisional magnetic pumping and/or turbulent energy cascading; the simulation in a steady-state, laboratory plasma of emission and turbulence related phenomena which occur on a microsecond time scale in intense particle beam sources and intense rf

sources of weapons interest; and plasma cloaking of military radar and directed microwave energy targets by magnetized plasmas. More information about these potential areas of application is given below.

The Production of RF Emissions

In Penning discharges, the emitting electrons and ions are trapped by a combination of electrostatic and magnetic trapping (see refs. 3, 4). The average particle lifetime is much longer than a single transit time, in constrast to travelling wave tubes where the emitting electrons are not trapped, and pass once through the interaction region in a single transit time. The trapping of electrons and ions in the emitting volume may lead to much higher efficiencies for rf emission than are possible in once-through devices like traveling wave tubes.

Experimental data from Penning discharges show that rf emissions occur over a very broad frequency band, from below 0.6 megahertz to frequencies as high as 2 GHz. Under the appropriate conditions, the emissions are capable of jamming AM/FM reception in Ferris hall, the building in which the UTK Plasma Science Laboratory is located. When the plasma operating conditions are just right, the rf emission is a virtually flat white noise spectrum over frequencies up to at least 1 GHz. The broad-band emission has the potential for development into a useful jamming tool, especially if the emitter were operated on a high power or pulsed basis.

The classical and modified Penning discharges may simulate physical processes that occur in intense particle beam sources and high power microwave sources, but do so in the steady state, and in plasmas of sufficiently

low density that conventional diagnostic instruments can be used to measure the characteristics of the plasma and of the resulting rf radiation. In some cases, the electric and magnetic geometry of the modified and classical Penning dicharges is similar to that of particle beam sources and/or high power microwave sources. It is such plasma parameters as the electron number density, the electrostatic potential, the electric field strength, and the duration of the discharge which differ. In our Penning discharges, relativistic effects are not important, as they would be in intense relativistic electron beam devices. Penning discharges may, however, provide useful information about physical processes in nonrelativistic proton beam sources and/or high power microwave sources, inwhich rf emission at the electron cyclotron frequency is not too important.

The Orbitron Submillimeter Maser

The Orbitron maser has presently been operated at wavelengths down to 0.3 millimeters in a pulsed mode, where the emitted power was about 1 watt. At lower frequencies, below 10 GHz, the Orbitron has been capable of producing more than 1 watt in the steady state. There appears to be no reason in principle why the Orbitron maser cannot be operated at powers of several hundred watts or even kilowatts at frequencies below 1 millimeter. A large power output of sub-millimeter radiation could have several applications of interest to the Air Force, including seeing through dust and fog, high resolution radar, and propagation of intense beams of radiant energy over large distances.

The penetration of electric field dominated plasmas by strong radial and axial electric fields is characteristic of the Orbitron microwave emitter and of Penning discharges. These electric fields allow the radiating ion and electron populations to be coupled directly to an external dc power supply, thus imparting energy to the radiating species in the same volume in which the rf emission originates. This contrasts with traveling wave tubes, where the electrons are accelerated to high velocity in an electron gun that is remote from the region in which the radiation originates. This factor may lead to higher efficiencies than are possible with traveling wave tubes and other microwave sources. This research may lead not only to mechanisms for creating plasmas at a very high steady state power density, but also to rf emitters more efficient than single-pass-through devices like the traveling wave tube.

Plasma Cloaking

It hardly seems necessary to elaborate on the desirability of making military targets disappear from radar screens. Our research on plasma cloaking should develop a background of basic physics that may make this possible. In the results presented in this proposal, we showed that very large attenuations of microwave power are possible in low density plasmas, with relatively small columnar densities, provided only that they are in a magnetic field.

In exploiting the resonance at the electron cyclotron frequency as a cloaking mechanism for radar signals, one should probably use a magnetic dipole as the magnetic containment configuration. If one were to install a

large superconducting coil which generates a dipolar magnetic field in an earth satellite, one may reasonably expect this dipole to accumulate from its surroundings, at orbital altitudes, enough plasma to be useful for cloaking purposes, just as the earth's magnetic field accumulates particles to form the magnetosphere. Broadband electromagnetic radiation approaching such a plasma-charged dipole would first enter relatively weak magnetic fields with low electron cyclotron frequencies of a few megahertz, and such low frequencies would be absorbed. In propagating toward the dipole, the electromagnetic radiation would progressively go through increasing magnetic fields corresponding to electron cyclotron resonance at higher and higher frequencies until, before it reached the surface of the spacecraft, the radiation traveled through a magnetic field sufficiently strong that it was above all expected radar frequencies. Any radiation in the ordinary mode which is not absorbed by its passage through the plasma may be scattered or reflected by interaction with the complicated dipolar plasma, or converted by reflection from the target to extraordinary mode radiation which would be absorbed on its way out. A patent on this concept is presently being sought.

The implementation of this plasma cloaking concept aboard aircraft and in the atmosphere would be more difficult, because of the necessity of generating the plasma in the dipolar magnetic field to absorb the incoming radiation, and the likelihood that the cloaking plasma would be attenuated or absorbed by the surrounding neutral atmosphere. This cloaking concept should also be effective in shielding military targets against directed microwave energy weapons.

Plasma Heating By Collisional Magnetic Pumping

There are only a handful of ways in which plasma can be heated to high power densities. We have recently demonstrated at the UTK Plasma Science Laboratory, for the first time, the experimental heating of a plasma by collisional magnetic pumping (our archival reprints on plasma heating by collisional magnetic pumping are in Appendix D.) This heating method allows coupling of RF energy to plasmas without the use of electrodes in contact with them. This new addition to known plasma heating techniques may be of value to the Air Force for applications requiring high power density or high energy density plasmas, including plasma cloaking, high power lasers, plasma materials processing of exotic aerospace materials, and other applications in which high power densities or high levels of plasma purity are required.

RESULTS OF OTHER CONTRACT ACTIVITIES

In addition to the three-year program of experimental research, the results of which are described above, this contract served as a vehicle to accomplish several additional objectives which were important to us here at the University of Tennessee, Knoxville, and which would not have been possible without the support of the Air Force Office of Scientific Research.

Development of the UTK Plasma Science Laboratory

Although development of the UTK Plasma Science Laboratory was not a goal of this research contract, AFOSR support has played important role in

elevating the research effort in experimental plasma physics at the University of Tennessee from a low level to a "critical mass" of student and faculty research effort in the areas of electric field dominated plasmas, plasma turbulence, and the interaction of RF radiation with high temperature plasmas. Part of the physical impact of Air Force support may be seen in Figures 1, 2, and 3 which show the UTK Plasma Science Laboratory before and after building up the classical Penning discharge, on which the research in this report was conducted. In addition to supporting the manpower required to set up and operate this steady-state research facility, the Air Force Office of Scientific Research has, through the DoD-University Research Instrumentation Program, provided an additional $233,000 for state-of-the-art equipment in 1985. This equipment is shown in Figure 4, and has had a major impact on the AFOSR and other contract research in the UTK Plasma Science Laboratory. The availability of training on this state-of-the-art equipment has not only attracted well qualified research assistants, but also regular graduate and upper division undergraduate students who have worked for us free, for the experience of using this state-of-the-art equipment. Support by the AFOSR was instrumental in making the UTK Plasma Science Laboratory, over the past nine years, into an important center in the southeastern United States for the experimental investigation of plasmas, and the training of students in plasma science and related disciplines.

Support of Graduate Study and Research at UTK

In 1980, there was no externally supported graduate study and research in experimental plasma physics on the UTK campus. With AFOSR support,

the UTK Plasma Science Laboratory now offers students at both the undergraduate and graduate level hands-on training in experimental plasma physics research with state-of-the-art equipment, using diagnostic methods which are at the forefront of university and national lab plasma physics research. The three-year AFOSR contract provided at least 9 person-years of half-time training at the graduate level, and an additional 10 person-years of half-time training to undergraduates who were hired as part of the AFOSR-UTK Undergraduate Research Fellowship Program.

The contributions of this contract to student support and training at UTK extend beyond the salary of 2 research assistants during this research program. During this period, this contract has, at no additional cost to the Air Force, supported research on four senior projects; work by three senior students on a three credit hour special projects laboratory course, each for at least one quarter; and a noncredit graduate laboratory course for a physics graduate student. In addition, contact with the experimental apparatus of this contract was incorporated into ECE 369, an undergraduate laboratory course involving several plasma physics experiments. Experimental data from the AFOSR experiment have been incorporated as homework and quiz problems in ECE 361, our undergraduate introductory course in plasma engineering, and as examples in ECE-NE 561-562, a graduate level course in plasma diagnostics.

Surplus DoD Equipment for Plasma Research

An activity which has greatly increased our inventory of RF and electronic test equipment has been the procurement of free, surplus

equipment under the DoD Surplus Propery Utilization Program. This program permits DoD contractors to obtain surplus equipment from DoD installations free of charge, and, since October, 1982, free of shipping charges. After 1987, the Surplus Property Utilization program was further simplified to allow principal investigators of DoD contracts to take the surplus property back to their laboratories with them, directly from the warehouse, without having to wait for clearance of the property transfer documents.

We have used our ONR contracts as legal vehicles for title to the surplus equipment. We have built up a large inventory, comprising 86 pages of computer printout, and several thousand items with a book (original cost) value of over 1.5 million dollars. All this equipment had been declared surplus at the federal installations where we obtained it. This program has allowed us to build up one of the best academic experimental research laboratories in the country in the area of RF interactions with plasmas, at no cost to the contract, or to the University of Tennessee.

Our first experience with this program was in December, 1982, when the Principal Investigator visited the Warner-Robins Air Force Base just south of Macon, GA, and obtained 24 items of surplus equipment for the UTK Plasma Science Laboratory. Since that time we have made at least one, and usually two, screening trips each year to military or other government installations within a four hour driving radius of Knoxville. These equipment scrounging trips, over a six year period, have allowed us to build up systematically an inventory of microwave hardware for the major frequency bands of interest for Air Force and naval radar systems. We have also obtained used, but serviceable, power supplies, electronic test equipment, signal generators, and

a wide variety of other expensive equipment that has greatly facilitated our research program for AFOSR, and has made possible measurements of a kind that would not have been financially possible without this program.

As an aside, it is very strange that this program is not much more utilized by principal investigators of DoD contracts. The property disposal officers at installations where we got our equipment have told me that microwave and electronic test equipment of the kind we obtained is something for which they had little call, and usually could not get rid of except at scrap prices. Nearly all the equipment which we obtained is at least ten years old, and does not meet state-of-the-art requirements, but nearly all of it is by major manufacturers of good reputation, is in working order, and is in calibration. Some systematic means should probably be found to inform DoD principal investigators of the opportunities provided by this program, perhaps by sending them an informational brochure when they obtain a DoD contract.

INTERACTIONS WITH OTHER RESEARCH PROGRAMS

Publications

The progress made and research results obtained under this contract have been systematically documented in Interim Scientific Reports and Status Reports; in the 28 conference presentations described in the next section of this report; in 20 archival papers presented at international scientific meetings and published in recognized scientific journals; and as final reports of completed work in the form of masters or Ph.D. theses which acknowledge AFOSR support, available through University Microfilms.

Copies of the Interim Scientific and Status Reports on this research program are already in the hands of the AFOSR; abstracts of the 28 oral and poster conference presentations are included in Appendix G; and reprints of the 20 archival scientific papers are included in Appendix E of this report. The abstracts, tables of contents,and title pages of the theses already published and supported by this contract are listed in Appendix H.

Conference Presentations

In addition to the archival and detailed full-length reports of completed work described in the previous section, and documented in Appendices D, E, and H, of this report, there were numerous conference presentations listed in Appendix F in which progress on this research program was reported to our professional peers. We have made it a practice to regularly present progress reports on the activities of this contract at the IEEE International Conference on Plasma Science, held on May of each year, and also at the annual meeting of the American Physical Society's Plasma Physics Division, usually held early November of each year. Most of these conference presentations were in poster format, and were progress reports covering he previous six months of activity under this contract.

Presentation of the work done under this contract at these conferences allowed us to interact with other investigators from such DoD laboratories as the Naval Research Laboratory, Edwards Air Force Base, the Kirtland Air Force Base, the Wright-Patterson Air Force Base, the Harry Diamond Laboratories, as well as many other DoE and DoD Principal Investigators of university contracts,at such universities as the University of Iowa, the

University of Wisconsin, the University of Texas at Austin, the Polytechnic University of New York, the University of Miami at Coral Gables, Texas Tech University, and others.

DoD Contracts at the UTK Plasma Science Laboratory

During the 3-year period of this report, the UTK Plasma Science Laboratory was supported by three DoD contracts. The first research contract to be awarded was ONR-N00014-80-C-0063 (Roth), Dr. Charles W. Roberson, Technical Monitor. This contract was granted on January 1, 1980, and extended through September 30, 1987. This contract was concerned with exploratory experimental investigations of the physical processes in electric field dominated plasmas generated in the steady state by a modified Penning discharge located in an axisymmetric magnetic mirror geometry. These investigations focused on RF emissions from the plasma, non-linear mode coupling of plasma fluctuations, axial electric field profiles, and other phenomena which may be related to, or have analogs in, the magnetosphere. This research program was extended to March 31, 1989 under ONR contract N00014-88-K-0174.

The second contract to be awarded to the UTK Plasma Science Laboratory was AFOSR-81-0093 (Roth), which started on March 15, 1981, and terminated on March 14, 1986. This contract was concerned with the investigation of physical processes in an electric field dominated plasma produced by steady-state operation of a classical Penning discharge with an approximately uniform axial magnetic field profile. The phenomena of particular interest in this investigaton were anomalous plasma resistivity,

axial electric field profiles, plasma turbulence, turbulent heating of ions, non-linear phenomena relating to energy dissipation in the plasma, and plasma heating by collisional magnetic pumping.

Professor Igor Alexeff of the UTK Department of Electrical Engineering has held AFOSR contract 82-0045, which terminated on March 14, 1986. This contract covered the development of a submillimeter microwave emitter based on the Orbitron configuration. Prof. Alexeff holds a US patent on this device, and under AFOSR sponsorship, has analyzed its operation and instabilities theoretically, while pursuing an experimental program which has achieved steady state operation, and generated wavelengths down to 0.3 millimeters. The Orbitron configuration has attracted interest at the Naval Research Laboratory, at the Hughes Research Laboratories, and other places where advanced research on microwave emitters is conducted.

The above two AFOSR contracts, AFOSR-81-003 (Roth), and AFOSR 82-0045 (Alexeff) were combined in a three-year follow-on contract, AFOSR-86-0100 (Roth) which supported, for a period of three years ending on March 14, 1989, the combined research efforts of J. R. Roth and Igor Alexeff, with Dr. Robert J. Barker of AFOSR as program manager. This Final Scientific Report covers work on this contract. Under Prof. Roth, the main thrust of this contract research was plasma cloaking and the theoretical and experimental study of collisional magnetic pumping as a plasma heating method; under Prof. Alexeff the thrust of his research program was further development of the Orbitron microwave emitter.

In addition to the above four contracts, Prof. J. Reece Roth was Principal Investigator of a 6-month, Short-Term Innovative Research Program Grant

from the Army Research Office (ARO) on "Corrosion Inhibition by Plasma Ion Implantation." This contract extended from July 1, 1988 to December 31, 1988 and was under the program management of Dr. Robert Reeber of the Materials Science Division of ARO. This work is being continued with UTK funds until June 1, 1989, after which time additional funding from the ARO will support a three-year effort in this area.

All three years of the contracts mentioned above have contributed to a critical mass of expertise and effort at the UTK Plasma Science Laboratory. Each of the contracts has contributed diagnostic methods and equipment to the common pool available to the graduate students and research programs supported by the AFOSR.

The AFOSR Undergraduate Research Fellowship Program

The UTK-AFOSR Summer Undergraduate Research Fellowship Program has been underway at the UTK Plasma Science Laboratory since the summer of 1985. It has benefited the AFOSR research program as well as that of the Navy. The objectives of the program are to train students in state-of-the-art methods and the use of state-of-the-art equipment; to make promising undergraduates familiar with DoD research and development; to introduce promising undergraduates to graduate study and research; to keep the manpower pipeline filled which supplies our country's future manpower pool for advanced research and development; to facilitate and contribute to ongoing university research programs funded by the Air Force at the UTK Plasma Science Laboratory; and to recruit promising undergraduate students

into graduate study and research at UTK and at the UTK Plasma Science Laboratory. The latter objective is ours, and is not that of the AFOSR.

The requirements of this program are that participants be U.S. citizens, that they be an undergraduate student of engineering or physics, that they must have completed a minimum of 8 quarters or five semesters toward an appropriate bachelors degree, that they be interested in hands-on experimental work, and that they have a grade point average of at least 3.20 on a scale of 4.0. In addition, we give preference to students who are interested in pursuing careers in plasma science or plasma physics.

The conditions of tenure for this program are that participants come to the UTK campus for a ten week program from early June to early August in the summer. They are expected to do full time work, 40 hours a week, for a gross pay of $3,000 for the ten weeks. We make available to them a UTK dormitory room for about $45.00 per week. We ask them to spend 20% of their effort on housekeeping activities in the UTK Plasma Science Laboratory, and devote 80% of their efforts over the summer on a single project which is designed either to take publishable data (some of our past summer students have appeared as co-authors on papers published out of the UTK Plasma Science Laboratory) or build up diagnostic or other equipment needed in our contract research. The students are expected at the end of the summer to write up a report on their projects, and present this orally to their peers during the last two days of the summer program. They are also expected to attend scheduled seminars every day for the first three weeks of the program, and at least once or twice a week after that. Most of these lectures are intended to give them background information which will be useful to them in making

career choices, selecting graduate schools, and understanding the physics behind projects in the UTK Plasma Science Laboratory. In addition, we offer equipment tutorials on various diagnostic equipment in the Plasma Lab and on some of our more sophisticated instruments.

This program offers a number of opportunities for students. They can obtain experience with state-of-the-art equipment which is not normally available to them in undergraduate physics or electrical engineering programs; they can learn useful skills in computer programming, vacuum technique, plasma diagnostics, microwave circuits, laboratory safety, etc. Their experience in the Plasma Lab gives them an opportunity to broaden their experience through orientation lectures, equipment tutorials, and weekly seminars involving faculty from the UTK Electrical & Computer Engineering Department who describe graduate level research in their respective areas. Our summer students also have an opportunity to observe graduate study and research at first hand, and to try their hand at research in plasma science or plasma physics. If they wish, they can earn academic credit for a senior project lab by registering for such a course at the UTK campus. In addition, several of our students in the past have used their summer project as the basis for a paper in a student paper competition. The student paper contest at the IEEE Southeastcon meeting has had a plasma-related entry from one of our summer students place first, second, or third each year for the past three years.

This program started in 1985 with a relatively modest effort because of the very short time we had to get it organized. Funds only became available in early May for a program that started in mid June. That first year, we had

six students and there was no off-campus recruiting because of insufficient time. The average GPA of those students was 3.4, and all but one went on to do graduate study. We had 14 weeks of half time activity and we did not have any orientation or equipment tutorial lectures during that first year. Of the six students, five were male and one female, and we only required them to work half time, or 20 hours a week.

In the summer of 1986, during the second year of the program, we had 26 applicants for 10 posts. Five women and twenty one men applied, and only four were from off campus. Of the final ten students, nine were male and one female and only one was from off campus. All the off campus recruiting was done by direct mail, and there was no recruiting through electrical engineering or physics department heads. We did our on campus recruiting by direct mail and bulletin boards. The average GPA that second year was 3.7, and at least eight of the ten went on to do graduate study. That summer program also lasted 14 weeks, at a half time level of effort, and a $500 per month salary. We had an orientation and final lecture and equipment tutorials organized that year.

During the third year of the program in the summer of 1987, we had 24 applicants for ten posts. Two of the applicants were female the rest male, and 21 of the 24 were from off campus. This improvement in off campus recruiting occured because we sent announcements, a brochure, and an application blank to 600 four-year EE department heads and 200 physics department heads in the eastern United States. Of the final ten students, one was female, and seven were from off campus. The on campus recruiting was done by bulletin boards only. The average GPA this third year was 3.54, and this time

we required a ten week summer program of full time, 40 hour a week work, at a salary of $2,500 for the ten week period.

In the summer of 1988, the fourth year of the program, we had 15 applicants with grade point averages between 3.5 and 4.0 on a scale of 4.0. Of these 15 applicants, one was female and 14 were male and twelve of the 15 applicants were from off campus. Of the students selected for the program there was one women and seven men, and five of the eight students were from off campus. The affiliations of the off campus students in 1988 included Auburn University, Bethany College, Brown University, Indiana University the College of Charleston in Charleston, SC, and UTK.

Other Presentations, Visits, and Reviews

During this contract, the Principal Investigator has interacted with a number of outside individuals and organizations. He has given invited talks at the IEEE Conference on Plasma Science in St. Louis, and at Cornell University, where he also interacted with John Nation and the ion beam plasma group. Other invited lectures and seminar presentations of the Principal Investigator are listed in Table II, below. Service by the P. I. on national boards and committees is listed in Table III. Some of this service is documented in Appendix I.

Table II

INTERACTIONS AT INVITED SEMINARS AND LECTURES

a) Interactions off the UTK campus

1. "Experimental Research on Plasma Instabilities and Turbulence at the University of Tennessee", Laboratory of Plasma Studies Seminar, Cornell University, Ithaca, New York, April 11, 1986.

2. Participant in the Gordon Conference on Plasma Chemistry, Tilton, NH, August 11-15, 1986.

3. "Recent Developments in Aneutronic Fusion for DoD Space Power and Propulsion Systems" Fusion Engineering Design Center Seminar, ORNL, Jan. 8, 1987.

4. "Experimental Research on Plasma Collisions, Heating, and Turbulence at the UTK Plasma Science Laboratory", Plasma Physics Seminar, Naval Research Laboratory, Washington, D.C. February 20, 1987.

b) Within the UTK Campus Community

1. Two lectures quarterly at the EE Department's Plasma Science Seminar Series.

2. "The Biological Effects of Electromagnetic Radiation-Issues and Research Opportunities" Microbiology Departmental Seminar, October 20, 1986.

Table III

INTERACTIONS WITH NATIONAL BOARDS AND COMMITTEES

Service on National Boards and Committees

1) Consultive panel member, Advanced Fuel Fusion Development Section for DoE Office of Fusion Energy's Technical Planning Activity (TPA) Report (Long-Range Planning Document), 1985-86.

2) Member, National Academy of Sciences-National Research Council's Committee on Advanced Fusion Power, sponsored by the Air Force Studies Board, 1986-87.

3) Chairman, Subcommittee on Space-Related Performance Parameters and Constraints of NAS-NRC's Committee on Aneutronic Fusion-Phase 1, 1986-87.

4) Workshop participant, NASA-Lewis Research Center's Lunar ^{3}He Workshop, April, 1988, Cleveland, Ohio.

5) Member, AFOSR Advisory Committee to the Air Force Geophysics Research Laboratory, Hanscom AFB, Massachusetts. May, 1988, Workshop on Atmospheric Interactions with Plasmas.

6) Invited speaker, ANS Minicourse on Fusion Applications in Space, Salt Lake City, UT, Oct. 1988.

In addition to the above interactions, we have been keeping in contact with other Principal Investigators and researchers in the general area of plasma heating and turbulence covered by this contract. At the Annual Meeting of the APS Plasma Physics Division and at the IEEE Conference on Plasma Science, we had occasion to interact with individuals doing similar research at the Naval Research Laboratory, at Cornell University, at the Polytechnic University of New York, at the Physics Department at the University of Miami at Coral Gables, at the Edwards Air Force Base, at the Kirtland Air Force Base, at the Harry Diamond Laboratories, at the University of Texas at Austin, at Texas Tech University at Lubbock, at the University of Wisconsin, and many other academic laboratories supported by AFOSR, ONR, and the Department of Energy.

Media Coverage

Unlike much larger metropolitan areas, the city of Knoxville is small enough that activities such as AFOSR support of research at the UTK Plasma

Lab attract media attention. Over this 3-year span of AFOSR support, our activities have resulted in much favorable publicity for the UTK Plasma Science Lab, the University of Tennessee at Knoxville, and the Air Force Office of Scientific Research. In Appendix K is included media stories which feature the AFOSR Research Program and the UTK Plasma Science Laboratory. Most of these stories are specifically about the AFOSR Research program. These news stories have done much to increase the visibility of the AFOSR within the UTK academic community, in the city of Knoxville, and in East Tennessee.

STAFFING

Faculty Investigator

This three year program of research utilized the services of three members of the UTK Electrical Engineering Department faculty, Prof. J. Reece Roth, Prof. Igor Alexeff, and Prof. David Rosenberg. Their professional background relevant to this contract is described briefly below, and the vitae and publications of Profs. Roth and Alexeff are included in Appendix A.

Professor J. Reece Roth In the past twenty-five years, Dr. Roth has authored or co-authored 107 archival publications, of which 70 were articles in refereed journals or conference proceedings, and the remainder of which were internally reviewed NASA reports. Dr. Roth has published in the Physics of Fluids, the Review of Scientific Instruments, the IEEE Transactions on Plasma Science, Physical Review Letters, Plasma Physics, Nuclear Fusion, the Journal of Applied Physics, the Journal of Fusion Energy, the Journal of Nuclear Instruments and Methods, the Journal of Spacecraft

and Rockets, Fusion Technology, the Journal of Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 89 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work.

While at the NASA Lewis Research Center, Dr. Roth made two pioneering contributions to fusion-related superconducting magnet technology. He was responsible for the basic design and distinctive features of the "Pilot Rig" superconducting magnet facility at NASA Lewis in Cleveland. This facility went into service in December, 1964, and was the first such facility ever to be used for plasma physics or controlled fusion research. Dr. Roth's second contribution in the magnet area was as the engineer responsible for the basic design and distinctive features of the NASA Lewis superconducting bumpy torus magnet facility. This facility was the first anywhere in the world to generate a toroidal magnetic field.

In studying the plasma which these facilities were designed to confine, Dr. Roth discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in the Pilot Rig in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity-equation oscillation has been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. 1. Dr. Roth as also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability).

His data were explained theoretically by Professor Igor Alexeff, and they jointly reported the discovery of this new instability in August, 1979.

Dr. Roth initiated research on the electric field bumpy torus concept, an approach to creating a plasma of fusion interest in which strong radial electric fields are imposed on a bumpy torus plasma, in such a way that they contribute to the heating, stability, and confinement of the plasma. Dr. Roth has authoritative knowledge of Penning discharges; the use of superconducting magnetic facilities in plasma and fusion applications; the continuity-equation oscillation and moving striations; ion heating and transport in a modified Penning discharge; high temperature plasma physics; fusion energy; and fusion technology.

Dr. Roth was the first to identify the physical mechanism responsible for ion heating in a modified Penning discharge, and the first to describe it. Dr. Roth's academic responsibilities have included teaching a required undergraduate course on plasma engineering from his own notes, a two-semester sequence on fusion energy, from his own textbook, and a two-semester doctoral level course on plasma physics.

Professor Igor Alexeff - Prof. Alexeff maintains an active consulting practice both nationally and internationally, conducts an active on-campus program of experimental plasma research, and teaches a variety of up-to-date plasma related courses on the graduate and undergraduate levels. In the past five years, his consulting activities have included regular interactions with the Isotope Separation Evaluation Group at K-25, Union Carbide at Oak Ridge, in which he has made significant classified contributions to the plasma isotope separation programp; consultations with the C.S.G. Inc. of Sucre,

Bolivia, in which he participated in the development of a more efficient electric motor based on the nonlinear properties of saturable iron; consultations with Motor Magnetics, Inc. of Cleveland, Ohio, on a new principle of electric motor design, consultations with the Ultra-Resonance Corp. of Los Angeles, on the subject of high beta tokamak research. He has been in great demand as an academic as well as an industrial consultant to help establish and collaborate with plasma research programs in other countries. These posts have included: Summer 1978; Visiting Professor, Physics Department, Universidade Federal Fluminense, Niteroi, Rio de Janeiro, Brazil ehere he helped set up a fusion research program; Summer 1976; Visiting Professor, Department of Physics, University of Natal, South Africa; Summer 1975; Visiting Professor, Physical Research Laboratory, Ahmedabad, India, where he helped set up plasma research effort. A result of this was a joint U.S.-India cooperative agreement funded by the NSF in the U.S., of which Dr. Alexeff was Principal Investigator. Spring, 1973; Visiting Professor, Institute of Plasma Physics, Nagoya, Japan, where he collaborated on several research papers on plasma waves. Dr. Alexeff's reearch activities at the University of Tennessee have resulted in a steady output of results on topics such as more efficient plasma lighting devices; submillimeter microwave power generation; joint discovery (with J. R. Roth) of the geometric mean plasma emission, a new mode of electromagnetic emission from plasmas which may be useful in communications; plasma-based isotope separators, plasma diagnostics, and fusion research.

From 1960 to 1971, Dr. Alexeff was Group Leader, Controlled Thermonuclear Division, Oak Ridge National Laboratory. At one point in his

career at ORNL. Dr. Alexeff directed three groups doing basic plasma research turbulent heating, and levitated toroidal multipole experiments. While at ORNL, Dr. Alexeff made fundamental contributions to the theory and experimental investigation of ion-acoustic waves (which can affect the perormance of plasma diodes, mercury-vapor rectifiers, and isotope separation devices), and to development of the "Burnout" experiment, which was an early steady-state electric field dominated plasma which heated ions to kinetic temperatures higher than any previously observed in the main-line fusion program of this country.

Professor David Rosenberg - Dr. David Rosenberg obtained his Doctor of Science in Engineering from New York University in 1964, and has been an Associate Professor in the UTK Electrical Engineering Department since September 1, 1967. Dr. Rosenberg has introduced and taught a wide variety of undergraduate and graduate courses at UTK in communications, including microwave electronics, electromagnetic wave propagation (at the graduate level), introductory microwave networks, microwave networks, guided waves, electromagnetic fields at the graduate level, and modern transform methods. Professor Rosenberg has consulted for the Army Research Offi Tullahoma, Tennessee, for the USAF Systems Command in Tullahoma, Tennessee, and for the NASA Marshall Space Flight Center in Huntsville, Ala. Prof. Rosenberg has been affiliated on a part time basis with the UTK Plasma Science Laboratory for the past two years, and has contributed to the development of our broadband, absolutely calibrated antennas, to our

microwave scattering diagnostic system, and to all aspects of our work that involve microwave or rf technique.

Student Training and Development

During this 3-year research program, travel funds were set aside for our graduate assistants, where this was necessary to their training and intellectual development. In the past 3 years, we have made it a custom to take at least our most senior AFOSR graduate research assistant with us to the IEEE and APS plasma meetings, and did this even on years when these meetings were west of the Mississippi River. On some years, we were able to take both AFOSR GRA's to these meetings.

We intend to continue our weekly plasma seminars, the program of which, for the past several academic years, is in Appendix C of this report. We also have broadened the horizons of our graduate research assistants by having them travel to other universities as well as to meetings. Our graduate research assistants have also accompanied Prof. Roth on screening trips for surplus equipment at various DoD installations, which are within a half-day's driving radius of Knoxville.

Student Manpower History

The 9-year staffing of this contract is shown on Table IV. The three years are shown in the first column, with the contract duration and personnel involved during that year in the second and third columns. The status of the personnel are listed on the fourth column, along with the duration of time during the 12 month contract that they were affiliated with it. The fraction of

Table IV
Contract Staffing History

Year	Contract Duration	Personnel	Status	Duration of Service Months	Yearly Fraction of Time	Highest Degree at UTK	Degree Research Done at UTK Plasma Lab	Now Working At	Current Status
1	3/15/86-3/14/87	J. Reece Roth	Prof., P.I.	12	0.25	---	----	---	---
		Igor Alexeff	Prof., Co-P. I.	12	0.25	---	---	---	---
		David Rosenberg	Faculty	12	0.125	---	---	---	---
		Fred Dyer	Res. Asso.	9	0.75	B.S.E.E.	---	Consultant, UTK Plasma Lab	Research Associate, UTK
		John Crowley	GRA	7	0.50	M.S.E.E.	Yes	Engineer, E.O.L., Oak Ridge	M.B.A. Student, UTK
		Mounir Laroussi	GRA	12	0.50	Ph.D.	Yes	Technical Univ. SFAX, Tunsia	Associate Professor Elect. Engr.
		Scott Stafford	GRA	5	0.50	M.S.E.E.	Yes	General Dynamics, NASA Ft. Worth, Texas	Avionics Engineer
		Mark Rader	GRA	9	0.25	B.S.E.E.	Yes (In Process)	UTK Plasma Lab	GRA, UTK
2	3/15/87-3/14/88	J. Reece Roth	Prof., P. I.	12	0.25	---	---	---	---
		Igor Alexeff	Prof, co-P.I.	12	0.25	---	---	---	---
		David Rosenberg	Faculty	12	0.125	---	---	---	---
		Fred Dyer	Res. Asso.	9	0.75	B.S.E.E.	---	Consultant, UTK Plasma Lab	Research Associate, UTK
		Mounir Laroussi	GRA	12	0.50	Ph.D.	Yes	Technical Univ., Sfax, Tunisia	Associate Professor Elect. Engr.
		Scott Stafford	GRA	12	0.50	M.S.E.E.	Yes	General Dynamics, Ft. Worth, Texas	Avionics Engineer
		LiLi Jiang	GRA	2	0.50	M.S., Physics	(in Process)	UTK Plasma Lab	GRA, UTK
		Mark Rader	GRA	12	0.25	B.S.E.E.	(in Process)	UTK Plasma Lab	GRA, UTK
3	3/15/88-5/14/89	J. Reece Roth	Prof. P.I.	12	0.25	---	---	---	---
		Igor Alexeff	Prof. Co- P. I.	12	0.25	---	---	---	---
		Mounir Laroussi	Postdoc	1.5	1.00	Ph.D	Yes	Technical Univ., Sfax, Tunisia	Associate Professor Elect. Engr.
		Mounir Laroussi	GRA	3	0.50	Ph.D	Yes	Technical Univ., Sfax, Tunisia	Associate Professor Elect. Engr.
		Fred Dyer	Res. Assoc.	13	0.75	B.S.E.E.	---	Consultant, UTK Plasma Lab	Research Associate, UTK
		John Crowley	GRA	3	0.50	M.S.E.E.	Yes	Engineer, E.O.L., Oak Ridge	M.B.A. Student, UTK
		Scott Stafford	GRA	8	0.50	M.S.E.E.	Yes	General Dynamics, Ft. Worth, Texas	Avionics Engineer
		LiLi Jiang	GRA	12	0.50	M.S., Physics	(in Process)	---	---
		Min Wu	GRA	4	0.50	M.S.E.E.	(in Process)	UTK Plasma Lab	GRA, UTK
		Philip Keebler	GRA	6	0.50	B.S.E.E.	(in Process)	UTK Plasma Lab	GRA, UTK
		F. Ghannadian	GRA	3	0.50	B.S.E.E.	---	UTK Plasma Lab	GRA, UTK

the time which they were paid to devote to the contract while they were employed under it is indicated in the 6th column. The highest degree obtained by the individual at UTK during or after his association with this contract is in the 7th column, and whether or not that individual did his thesis research in the UTK Plasma Lab is indicated in the 8th column. The penultimate column lists the organization at which the individual is now working, or was last known to be working, and his current status at that organization is indicated in the last column.

Prior to 1980, there was a very low level of externally supported graduate study and research in experimental plasma physics on the UTK campus. With Air Force and ONR support, the UTK Plasma Science Laboratory now offers students at both the undergraduate and graduate level hands-on training in experimental plasma physics research with state-of-the-art equipment, using diagnostic methods which are at the forefront of university and national lab plasma physics research. The research effort summarized in this report supported faculty and graduate student assistants at the levels indicated in Table IV.

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APPENDIX A

Resumes of Principal Investigators

September, 1988

PROFESSIONAL RESUME

J. Reece Roth
Department of Electrical and Computer Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2100
(615) 974-4446
FTS 855-4446

I. PERSONAL

Birthdate: September 19, 1937
Marital Status: Married, two children
Health Status: No physical handicaps

II. EDUCATIONAL

College: Massachusetts Institute of Technology, graduated in June 1959 with a S.B. in Physics.

Graduate: Entered Cornell University in September 1959, graduated in June 1963 with the Ph.D. Major: Engineering Physics. Minor subjects: Magnetohydrodynamics and Astrophysics.

III. PROFESSIONAL EXPERIENCE

1. 1963 to 1978, Member of the Plasma Physics Branch of the Physical Science Division at the NASA Lewis Research Center in Cleveland, Ohio. Was Principal Investigator of the NASA Lewis Bumpy Torus Project.

2. September 1978 to June, 1982. Visiting Professor of Electrical Engineering, University of Tennessee, Knoxville. Principal Investigator of two research contracts in the field of electric field dominated plasma, one with the ONR, the other with AFOSR. In addition to research, taught a junior level course on plasma engineering, a graduate sequence on fusion technology, plasma diagnostics, and physics of fusion, also taught one-week minicourses on fusion energy and fusion diagnostics.

3. June 1982 to August, 1983. Research Professor, Department of Physics.

4. September 1983 to present. Professor of Electrical Engineering and Chairman of the departmental Plasma Engineering Curriculum Committee. Continuation of contract research, and teaching of a graduate course sequence in Plasma Diagnostics, a senior-level course "Introduction to Fusion Energy," and a junior-level course in Plasma Engineering. Published a textbook, "Introduction to Fusion Energy" in December, 1986.

IV. CONTRACTS AND EXTERNAL SUPPORT

Principal Investigator of contracts with ONR, AFOSR, ARO and TVA which, since 1980, will bring in $1,437,870 by the time present contracts run out in early 1989. These contracts will yield a total overhead of $368,385 to the University at that time. They also have provided $278,464 in special equipment grants which have been used to purchase new, state-of-the art diagnostic equipment for the UTK Plasma Science Laboratory. These contracts also made it possible to acquire surplus instruments and equipment from the Department of Defense with a replacment value exceeding one million dollars. These contracts will provide 4.50 man-years of faculty support and 35.7 student-years of support when the last contract runs out.

V. HONORS, AWARDS, AND LISTINGS

Relevant student honors include a four-year Alfred P. Sloan Scholarship at M.I.T., Presidency of the M.I.T. Rocket Research Society, the 1957 American Rocket Society-Chrysler Corporation's Student Award, and a Ford Fellowship at Cornell. Life Member of Sigma Xi, Fellow of IEEE, Senior member of AIAA and co-recipient of one of NASA's "Awareness" awards to the Bumpy Torus Project. Listed in "Who's Who in the Midwest," 1970 to 1978 Editions; "Who's Who in the South and Southwest, "17th Edition, Who's Who in America, 43rd and 44th Editions.

VI. PROFESSIONAL SOCIETY MEMBERSHIPS

1. Fellow of the IEEE
2. Life member of Sigma Xi
3. Life member of the AAAS
4. Senior Member of the AIAA
5. Member of the American Physical Society
6. Member of the American Nuclear Society
7. Member of American Society for Engineering Education
8. Member of the IEEE Nuclear and Plasma Sciences Society
9. Member of the Archaeological Institute of America
10. Member of the University Fusion Association

VII. PROFESSIONAL SOCIETY ACTIVITIES

1. Associate Editor, IEEE Transactions on Plasma Science, 1973-1987.
2. Elected Member-at-Large of Administrative Committee, IEEE Nuclear and Plasma Sciences Society, 1974-77.
3. Secretary, NPSS Administrative Committee, 1975.
4. Organizing Committee, IEEE Plasma Science and Applications Committee, 1971-73.
5. Elected Member, Executive Committee of IEEE Plasma Science and Applications Committee, 1974-77, 1980-82, 1985-87.
6. Member of the Program Committee, IEEE International Conferences on Plasma Science, 1974, 1975.

7. Member, Executive Committee, Northern Ohio Section of the American Nuclear Society, 1975-1978.
8. Member, AIAA Plasmadynamics Technical Committee, 1979 to 1981.
9. Director, and Member of Executive Committee, East Tennessee Section of the IEEE, 1982-83, 1988-90.
10. Vice Chairman, East Tennessee Section of the IEEE, 1983-84.
11. Chairman, East Tennessee Section of the IEEE, 1984-85.
12. Vice President, UTK Chapter of Sigma Xi, 1984-85.
13. President, UTK Chapter of Sigma Xi, 1985-86.
14. Educational Activities Chairman, Tennessee Council of IEEE Region III, 1986-87.
15. General Chairman, IEEE Southeastcon '88, 1985-88.

VIII. OTHER PROFESSIONAL ACTIVITIES

A) Service on National Boards and Committees

1) Consultive panel member, Advanced Fuel Fusion Development Section for DoE Office of Fusion Energy's Technical Planning Activity (TPA) Report (Long-Range Planning Document), 1985-86.

2) Member, National Academy of Sciences-National Research Council's Committee on Aneutronic Fusion-Phase I, 1986-1987.

3) Member, Scientific Advisory Committee to the Air Force Geophysics Laboratory, Hanscom AFB, MA.

4) Member, Fusion Power Working Group at the NASA Lunar Helium-3 Fusion Power Workshop, April 25-26, 1988, Cleveland, OH

B) Consulting

1) Westinghouse Corporation - Consultation on the preparation of their proposal for the EBT-S Prime Contract. April 30, 1980 to December 31, 1980.

2) Tennessee Valley Authority - Was hired to give a series of seven five-hour lectures on fusion energy for the benefit of staff of TVA's Power Office in Chattanooga, Sept. 28 to Nov. 16, 1982.

3) Tennessee Valley Authority - Consultant and Principal Investigator of two closely linked contracts which provided retainer-type consulting and support for one graduate student. January 1, to December 31, 1983.

4) Department of Physics and Astronomy, University of Maryland, College Park, Maryland - Reviewer of proposals submitted to the Air Force Office of Scientific Research (AFOSR), with them acting as intermediary, November 1985 to present.

5) Army Research Office - Consultant and Principal Investigator of a 6-month Short Term Innovative Research contract which supported two GRA's, July 1 to Dec. 31, 1988.

6) BDM Corporation, McLean, VA - Consultant on potential applications of fusion energy to the SDI program, February, 1988 to present.

C) Services as Reviewer

Have served as a reviewer for proposals or manuscripts for the following organizations and journals:

1) Tennessee Valley Authority

2) National Science Foundation, Engineering Directorate

3) Air Force Office of Scientific Research

4) IEEE Transactions on Plasma Science

5) Fusion Technology

6) Plasma Physics and Fusion Energy

7) Nuclear Fusion

8) Aerospace Engineering and Applied Mechanics

9) Journal of Applied Physics

IX. PROFESSIONAL ACCOMPLISHMENTS

In the past twenty years, Dr. Roth has authored or co-authored 110 archival publications, of which 41 were articles in refereed journals, 32 were full-length papers in reviewed conference proceedings, and the remainder of which were internally reviewed NASA reports. Dr. Roth has published in the Physics of Fluids, the Review of Scientific Instruments, the IEEE Transactions on Plasma Science, Physical Review Letters, Plasma Physics, Nuclear Fusion, the Journal of Applied Physics, the Journal of Fusion Energy, the Journal of Nuclear Instruments and Methods, the Journal of Spacecraft and Rockets, Fusion/Technology, the Journal of Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 100 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work.

While at the NASA Lewis Research Center, Dr. Roth made two pioneering contributions to fusion-related superconducting magnet technology. He was responsible for the basic design and distinctive features of the "Pilot Rig" superconducting magnet facility at NASA Lewis in Cleveland. This facility went into service in December, 1964, and was the first such facility ever to be used for plasma physics or controlled fusion research. Dr. Roth's second contribution in the magnet area was as the engineer responsible for the basic design and distinctive features of the NASA Lewis superconducting bumpy torus magnet facility. This facility went into service in 1972, and was the first superconducting magnet facility anywhere in the world to generate a toroidal magnetic field.

In studying the plasma which these facilities were designed to confine, Dr. Roth discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in the Pilot Rig in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity- equation oscillation has been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. I. Dr. Roth was also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability). His data were explained theoretically by Professor Igor Alexeff, and they jointly reported the discovery of this new instability in August, 1979.

Dr. Roth initiated research on the electric field bumpy torus concept, an approach to creating a plasma of fusion interest in which strong radial electric fields are imposed on a bumpy torus plasma, in such a way that they contribute to the heating, stability, and confinement of the plasma.

Dr. Roth has authoritative knowledge of Penning discharges; the use of superconducting magnet facilities in plasma and fusion applications; the continuity- equation oscillation and moving striations; ion heating and transport in a modified Penning discharge; high temperature plasma physics; fusion energy; and fusion technology. Dr. Roth was the first to identify the physical mechanism responsible for ion heating in a modified Penning discharge, and the first to describe it. Dr. Roth's academic responsibilities have included teaching a required undergraduate course on plasma engineering from his own notes, a one-year senior and graduate level sequence on fusion energy, also from his own notes, a one year graduate course in Plasma Diagnostics which includes a laboratory, a doctoral level course on advanced plasma physics, and intensive one-week minicourses on Fusion Diagnostics and Fusion Energy, which have attracted students from all over the United States and Canada. He has recently published a senior and first year graduate level textbook, "Introduction to Fusion Energy."

BIOGRAPHICAL SKETCH
Igor Alexeff

1. Name and Date of Birth:

   Igor Alexeff
   January 5, 1931

2. Academic Rank:

   Professor of Electrical Engineering

3. Degrees, With Field, Institution and Date:

   Professional Engineer, Registered 1978, State of Tennessee.
   University of Wisconsin, Ph.D - 1959.
   Harvard University, Cambridge, Mass., Bachelors Degree - 1952.

4. Number of Years Service on this Faculty: 17

   Original Appointment - September, 1971

5. Other Related Experience - Teaching and Industrial:

   Westinghouse Research Lab. - Nuclear Physics Research, 1952-53

   University of Zurich, Switzerland-Nuclear Physics Research, 1959-60.

   ORNL Thermonuclear Division Plasma Physics Research, 1960-July 31, 1971.

   University of Tennessee, 1971-Present

   Visiting Professor:

   1973 Institute of Plasma Physics, Nagoya, Japan

   1975 Physical Research Laboratory, Ahmedabad, India

   1976 University of Natal, South Africa

   1978 Universidade Federal Fluminense, Rio de Janeiro, Brazil

6. Consulting:

   Oak Ridge National Laboratories, Motor Magnetics, Hughes Research Labs, Vamistor Corp. (Sevierville, Tn), Perceptics Corp.

7. States in Which Registered: Tennessee

8. Scientific and Professional Societies of which a Member:

American Physical Society

Sigma Xi

IEEE

University Fusion Association

9. Honors and Awards:

Secretary, Treasurer, Vice President, President, Oak Ridge section of the IEEE

Fellow IEEE

Fellow American Physical Society

Secretary-Treasurer American Physical Society Plasma Physics Division
'83-84

Member - Steering Committee of University Fusion Association ('82-'83-'84)

Listed in Who's Who in America

Listed in Who's Who in the World

Listed in Who's Who in South and Southeast

Guest, Russian Academy of Science - paid two visits

Chairman - IEEE Plasma Society, '83, '84

Secretary, IEEE Plasma Society (1982, '81, '80)

Member, MENSA

Vice President, IEEE Nuclear and Plasma Sciences Society 1983

Vice President, Southern Appalachian Science Fair '82-'83, President, '84-'85

Chairman 1974 Gorden Conference on Plasma Physics

Organizer 1976 School of Plasma Physics Ahmedabad, India (with USNSF support - co-chaired with Dr. Bimla Buti)

Organizer, 1st IEEE International Conference on Plasma Science
Knoxville (1974)

Member, IEEE Fellow Committee '83-'84'-'85-'86
IEEE NPSS Fellow Committee Survey Group 1987-present.

University of Tennessee Chancellor's Research Scholar, 1984.

IEEE Centinnial Medal Awarded 1984.

President, Tennessee Inventors Association, 1984.

IEEE Outstanding Engineer in the Southeast, 1987.

10. List any specific programs in which faculty member has participated to improve teaching and professional competence:

    Speaker - WATTec
    Sponsored research activities
    Speaker - IEEE Knoxville Section
    Speaker - IEEE Oak Ridge Section

11. Languages-German, Russian, Basic

12. <u>Recent Contracts</u>

    Sponsor
    AFOSR
    Project
    "Millimeter Microwave Emission by use of Plasma Produced Electrons Orbiting a Positively - Charged Wire."
    Funding:
    $78,000 November 15, 1983 - November 15, 1984

    Sponsor
    NSF
    Project
    "Engineering Aspects of Plasma Waves"
    Funding
    $37,530 December 15, 1982 - December 15, 1983

13. Ph.D. Students

    Past:

Akira Hirose	Univ of Saskatchewan
Kent Estabrook	Livermore
Mel Widner	Sandia
Osamu Ishihara	Texas Tech
Marshall Saylors	NSA
Bill Wing	ORNL
Larry Barnett	Univ of Utah
Wlodek Nakonieczny	Microsoft
Phil Ryan	ORNL

Monty Smith UTSI

Present:

Mark Rader
Tim Bigelow (ORNL)

14. Recent invited papers

1. "Millimeter Microwave Production from a Maser by use of Electrons Orbiting Positively-Charged Wire (Synthetic Atoms).
Igor Alexeff, Division of Plasma Physics Twenty-Third Annual Meeting, American Physical Society, New York, NY (12-16 October 1981).

2. "Elementary Plasma Demonstrations Under $10.00 Each"
Igor Alexeff.
San Francisco Meeting of the American Physical Society, 25-28 January, 1982.

3. "Recent Results on the Orbitron Maser", 10th International Free-Electron Laser Conference August 29-September 2, 1988, Jerusalem, Israel (IEEE), paper 11/2

15. Patents in Force (3) - High Voltage Opening Switch, Microwave Masers

16. Technical Record:

At present, I am a full professor of Electrical Engineering at the University of Tennessee, Knoxville, and am a registered professional engineer in the state of Tennessee. I have several industrial consulting contracts. My present university research is sponsored from these contracts, the University, The U.S. National Science Foundation, and the U.S. Air Force. The work concerns plasma engineering, plasma isotope separation, electromagnetics, and optics.

In earlier times, I spent 10 years (1960-1971) at the Oak Ridge National Laboratory in fusion research. During this period I was at one time group leader of 3 groups at once, was responsible for a budget of over $500,000/year, and authored 50 refereed papers.

I spent one year at Westinghouse (1952-1953), where I developed a neutron energy spectrometer that contributed to nuclear submarine engine development.

I have about 100 refereed published papers in the fields of Plasma Physics, Plasma Engineering, Nuclear Physics, and Education in the above fields. My major discoveries were in the fields of plasma waves, plasma turbulence, and plasma heating.

Finally, I have been able to help some very fine undergraduate and graduate students start their careers. This is probably my most important contribution to society.

17. Publications:

Book *High-Power Microwave Sources* (with Victor L. Granatstein), (Artech House, Boston, London 1987), (Alexeff co-edited the book and wrote chapter 8 "The Orbitron Microwave Maser")

Papers:

1948
Electronic Relay, Radio Craft, March 1948, p. 40.

1955
The Scattering of 4.4 Mev Neutrons by Iron and Carbon, (with B. Jenkins, J. Weddell, and R. L. Hellens) Phys. Rev. 98, (1955).

1955
Evapor-Ion Pump Performance with Noble Gases (with E. C. Peterson) Vacuum Sump. Trans. p. 87, 1955.

1955
Evapor-Ion Pump Development, (with M. F. Bina and R. M. Sanders), Phys. Rev. 98, 251A (1955).

1955
Evapor-Ion Pump Performance with Noble Gases, (with E. C. Peterson), Phys. Rev. 100, 123A (1955).

1957
An Easily Remembered Derivation of PVR-C for the Student, AM.J. Phys. 25, 488 (1957).

1959
Polarization in Proton-Proton Scattering at 3.5 Mev, (with R. I. Brown, R. A. Lux, S. J. Moss, and W. Haeberli), Bull. AM. Phys. Soc. 4. 253 (1959).

1960
Attempts of Produce H 25 by Charge Exchange, Proc. Inter. Symp. Polarization Phenomens of Nucleons, Basel, p. 134 July, 1960.

1960
Polarization in Proton-Proton Scattering Near 3.3 Mev. (with W. Haeberli) Nuclear Physics 15, 609 (1960).

1961
A Vacuum Manometer Using Ultra-Violet Light, Second Inter. Congress Inter. Organization for Vaccum Sci. Technol. Oct. 1961.

1961
Discovery of Ion-Acoustic Waves. Igor Alexeff, and R. V. Neidigh, Phys. Rev. Letters, 7, 223.

1961
Observation of Ionic Sound Waves in Gaseious Discharge Tubes. (with R. V. Neidigh) Proc. Fifth Inter. Conf. Ionization Phenomena P. 1523, 1961.

1962
A Way to Measure Plasma Density-The Plasma Sweeper (with R. V. Neidigh) Proc. 3rd Symp., Eng. Aspects of Magnetohydrodynamics, Mar. 1962.

1962
Experiments concerning The Magnetic Confinement of a Cold Plasma (with R. V. Neidigh and C. D. Shipley) J. Nucl. Energy. Part C, 4, 263 (1962).

1962
Experimental Observation of Plasma Electron Pressure (with R. V. Neidigh) Phys. Rev. 127, 1. (1962).

1962
A Vacuum Namometer Using Ultraviolet Light, pp. 472-75 in Trans. 8th Vacuum Symposium and 2nd International Congr. Vacuum Technology. Ed. L. E. Preuss, Macmillan, New York, 1962. (Work Done at the Physical Institute, University of Zurich, Switzerland, and Supported by the U. S. National Science Foundation. Patent Assigned to the high voltage Engineering Corp., Burlington.

1962
A Device to Measure the Rate of Flow of a Plasma, The Plasma Eater, (with R. V. Neidigh), Bull. AM. Phys. Soc. 7, (4), (1962).

1962
Random Injection into a Mirror Geometry, (with R. V. Neidigh and E. D. Shipley), Bull. Am. Phys. Soc. 7, (6), (1962). A-M3.

1962
Ionic Sound Waves in an Electromagnetic Isotope Separator, (with A. M. Veach and O. C. Yonts), AM. Phys. Soc. 7, (1962).

1963
Direct Measurement of Ionic Sound Wave Velocity (with W. D. Jones) Intern. Ionization Phemomena Gases, proc. 6th, Paris, July, 1963.

1963
Observations of Ionic Sound Waves in Plasmas-Their Properties and Applications, (with R. V. Neidigh) Phys. Rev. 129, 516 (1963).

1963
Optimum Energy For Plasma Confinement (with R. V. Neidigh and E. D. Shipley) Phys. Fluids 6, (1963).

1963
A Plasma Flowmeter. The Plasma Eater (with R. V. Neidigh) Nucl. Fusion 3, 23 (1963).

1963
Proceedings Sixth International Conference on Ionization Phenomena in Gases, Paris 1963. (To be Published).

1963
A Way to Measure Plasma Denisty-The Plasma Sweeper, (with R. V. Neidigh), pp. 141-52, Eng. Aspects of Magnetohydrodynamics, 3rd., Symp., Gordon and Breach, 1963.

1963
Plasma Denisty Measurement by Casting a Shadow in Evaporated Gold. (with R. V. Neidigh and W. F. Peed), Bull. Am. Phys. Soc. 8, (1963). F4.

1963
Hot Electron Plasma By Beam-Plasma Interaction, (with R. V. Neidigh,
W. F. Peed and E. D. Shipley). Phys. Rev. Letters 10, 273, (1963).

1964
Beam-Plasma Interaction Experiments and Diagnostics (with R. V. Neidigh and W. F. Peed) Phys. Rev. 136, (1964).

1964
Experiments with Ioffee Magnetic Fields, (with R. V. Neidigh), Bull. Am. Phys. Soc. 9, 327 (1964).

1964
The Velocity of Moving Striations in Discharge Tubes as a Function of Gas Pressure, (with W. D. Jones), Bull, AM. Phys. Soc. 9, 469 (1964).

1964
Some Effects of a Magnetic Field on Coulobm Scattering, (with R. V. Neidigh and D. Montgomery). Bull. Am. Phys. Soc. 9, 325 (1964).

1964
Observations of Discharge-Tube Striations Using an Image Converter, (with W. D. Jones and R. V. Niedigh), Bull. Am. Phys. Soc. 9, 323 (1964).

1964
A Possible Source of the Energetic Ions emitted From the Pressure Gradient Arc, (with R. V. Neidigh), Bull. Am. Phys. Soc. 9, 469 (1964).

1964
Observation of Burnout in a Steady-state Plasma, (with R. V. Neidigh), Phys. Rev. Letters 13, 179 (1964).

1965
Stroboscopic Shutter for Visulaay Studying Plasma Oscillations, (with W. D. Jones, and R. V. Neidigh), Rev. Sci. Instr. 36, 44-47, 1965.

1965
Sampling Oscilloscope as a Coherent Wide-Band Detector, (with P. Bletzinger, A. Garscadden and W. D. Jones) J. Sci. Inst. 42, (1965).

1965
Some Stabilized Plasma Experiments, (with R. V. Neidigh), Phys. Fluids 8, (1965).

1965
Collisionless Ion-Wave Propagation and Determination of the Compression Coefficient of Plasma Electrons. (with W. D. Jones). Phys. Rev. Letters 15, 286-88. (1965).

1965
Study of Ionic Sound Wave Pulses Using Electronic Noise Rejection. (with W. D. Jones). Bull. Am. Phys. Soc. 10, 200 (1965). (Presented by Alexeff at Culham Laboratory Study Group on Plasma Waves, Sept. 21-25, 1964-- No Formal Paper Prepared).

1965
Burnout By Beam-Plasma Interaction, (with R. V. Neidigh and W. F. Peed), Bull., Am. Phys. Soc. 10, 523 (1965).

1965
Properties of Ionic Sound Waves in a Collisionless Discharge-Tube Plasma, (with W. D. Jones,) Bull, Am. Phys. Soc. 10, 509 (1965).

1965
Observation of Cutoff of Ionic-Sound-Wave Propagation Near the Ion-Plasma Frequency, (with W. D. Jones), Bull, Am. Phys. Soc. 10, 509 (1965).

1966
Plasma-Density Measurement in a Hollow-Cathode Arc by Arc Reversal, (with W. Halchin, W. D. Jones and J. F. Potts), ORNL-4010, Sept. 1966.

1966
Beograd, Yugoslavia, Aug. 1965 (ED. By B. Perovic and Tosic), Gradevinska Knjiga, Beogra Yugoslavia, 1966.

1966
A Simple Thermal Instability in Discharge Tubes--A Possible Cause of Moving Striations, Bull. Am. Phys. Soc. II, 551 (1966).

1966
Plasma Heating and Burnout in Beam-Plasma Interaction, (with W. D. Jones, R. V. Neidigh, W. F. Peed and W. L. Stirling), Proc. 2nd Conf. Plasma Physics and Controlled Nuclear Fusion Research, Culham, England, Sept. 6-10, 1965, IAEA, Vienna. 1966 Vol. II, P. 781. Sti/Pub/111. (Cn-21/102).

1966
Neutron Source Strengths in Burnout V, (with R. V. Neidigh and W. F. Peed), Bull, Am. Phys. Soc. II. 575 (1966).

1966
Iron-Core Minimum B Magnet, (with W. Halchin), pp. 106-09 Proc. Engineering Problems of Controlled Thermonuclear Research Symp., Gatlinburg, Tenn., Oct. 1966, Conf-661016.

1966
Electron Emitting and Electron-Collecting Probes as Ion Wave Detectors, (with W. D. Jones), Phys. Letters 20, 269-71 (1966).

1966
Development of a Hot-Electron Plasma Blanket, (with W. L. Stirling, R. V. Neidigh + V. J. Meece), J. Nucl. energy. Pt. C. 8, 157-58 (1966).

1966
Iron-Core Electromagnet Producing a Magnetic Well with Nonzero Minimum Fro Plasma Confinement. J. Appl. Phys. 37, 2166).

1966
Plasma Decay Technique to Measure Density in Discharge Tubes, (with W. D. Jones and J. Lohr), Phys. Fluids 9. 1403-06 (1966).

1966
Varying Plasma Electron Temperature in Discharge Tubes by a Simple Auxiliary Electrode. (with W. D. Jones), Appl. Phys. Letters 9, 77-79 (1966).

1966
Observations on the Velocity of Moving Striations. (with W. D. Jones), Phys. Fluids 9. 1871-72 (1966).

1966
Alternative Method for Exciting Electron Plasma Oscillations with Transverse Electromagnetic Waves, (with D. Montgomery), Phys. Fluids 9, 2076-77 (1966).

1966
Plasma Heating and Burnout in Beam-Plasma Interaction, (with W. D. Jones, R. V. Neidigh, W. F. Peed and W. L. Stirling), Vol. 2, pp. 781-99, Plasma Physics and Controlled Nuclear Fusion Research, Proc. 2nd Conf., Culham, England, Sept. 1965 Intern. at Energy Agency, Vienna, 1966.

1966
Parametric Excitation of Transverse Waves in a Plasma, (with D. Montgomery), Phys. Fluids 9, 1362-66 (1966).

1966
A Study of the Properties of Ionic Sound Waves, (with W. D. Jones), pp. 330-35, Phenomena in Ionized Gases, Proc. 7th Intern. Conf., Beograd, Yugoslavia, 1966.

1966
Simple Momentum Probe for Plasma Studies, (with W. D. Jones, D. Montgomery and M. Rankin). pp. 62-66, Phenomena in Ionized Gases, Proc. 7th Intern. Conf.

1967
Electron Temperature Variation Induced Effects and Landau Damping of Ion Acoustic Waves, (with W. D. Jones and D. Montgomery), ORNL, April 1967.

1967
Production of D-D Reactions by Beam-Plasma Interaction in the Steady State, (with W. D. Jones and R. V. Neidigh), Phys. Rev. Letters 18, 1109-12 1967.

1967
Electron-Temperature Variation Induced Effects and Landau Damping of Ion Acoustic Waves, (with W. D. Jones, and D. Montgomery), pp. 371-95, Physics of Quiescent Plasmas, Proc. Conf., Frascati, Italy, Jan. 1967, Laboratori Gas Ionizzati, Associazione Euratom-Cnen, 1967.

1967
Observation of the Ion-Temperature Contribution to the Ion-Acoustic Wave Velocity, (with W. D. Jones, and M. G. Payne), Bull, Am. Phys. Soc. 12, 770 (1967).

1967
Energetic Particle Scattering by Laboratory Plasmas, (with D. Montgomery and C. Roque), Bull. Am. Phys. Soc. 12, 749 (1967).

1967
Demonstration of Landau Damping of Ion-Acoustic Waves in Discharge- Tube Plasmas, (with W. D. Jones and D. Montgomery), Bull. Am. Phys. Soc. 12, 770 (1967).

1967
Controlled Landau Damping of Ion-Acoustic Waves, (with W. D. Jones), Bull, Am. Phys. Soc. 12, 711-12 (1967).

1967
Landau Damping of Ion-Acoustic Waves Produced by a Ligh Contaminant. (with W. D. Jones and D. Montgomery), p. 357, Phemomena in Ionized Gases, 8th Intern. Conf., Vienna, Austria, Sept. 1967, Inter, At. Energy Agency, Vienna, Austria, 1967.

1967
Dispersion of Ion-Acoustic Waves, (with K. Lonngren, D. Montgomery and W. D. Jones), Phys. Letters 25A, 629-30 (1967)

1968
Oscillations Present in Plasma-Electron Heating by an Electron Beam, (with G. E. Guest, D. Montgomery, R. V. Neidigh and D. J. Rose), Phys. Rev. Letters 21, 344-47 (1968).

1968
Azimuthally Localized Fluctuations in a Levitated Toroidal Quadrupole, (with M. Roberts and W. Halchin), Phys. Letters 26A, 590-91 (1968).

1968
Excitation of Pseudowaves in a Plasma Via a Grid, (with W. D. Jones and K. Lonngren), Phys. Rev. Letters 21, 878-81 (1968).

1969
Experimental Stron Turbulent Heating, (with R. V. Neidigh, G. E. Guest,
W. D. Jones, D. C. Montogomery, D. J. Rose and W. L. Stirling). Book. Proc. Plasma Physics and Controlled Nuclear Fusion Research, 3rd, IAEA Conf., Novosibirsk, USSR, Aug. 1968, IAEA, Vienna, Austria, Vol. 2, 693- 708, 1969.

1969
ORNL Leviatated Toroidal Multipole Program, (with M. Roberts, R. A. Dory, W. Halchin and W. L. Stirling). Book. Proc. Plasma Physics and Controlled Nuclear Fusion Research, 3rd IAEA Conf., Novosibirsk, USSR, Aug. 1968, IAEA, Vienna, Austria, Vol. 2, pp. 651-665, 1969.

1970
I. Alexeff, W. D. Jones and M. Widner, "Multiple Pseudowaves Produced by a Single Voltage Pulse, " The Physics of Fluids, Vol. 13, No. 6, pp. 1519-1524, June, 1970.

1970
W. L. Stirling, M. Roberts, and I. Alexeff, "Effects of Introducing Supports in a Levitated Toroidal Quadrupole," The Physics of Fluids, Vol. 13, No. 7, pp. 1888-1889, July, 1970.

1970
I. Alexeff, K. Estabrook, A. Hirose, W. D. Jones, R. V. Neidigh, J. N. Olsen, F. R. Scott, W. L. Stirling, M. M. Widner, and W. R. Wing. "Understanding Turbulent Ion Heating in the Oak Ridge Mirror Machine, "Burnout V" Physical Review Letters, Vol. 25, No. 13, pp. 848-851, September, 1970.

1970
M. Widner, I. Alexeff, W. D. Jones and K. E. Lonngren, "Ion Acoustic Wave Excitation and Ion Sheath Evolution," The Physics of Fluids, Vol. 13, No. 10, pp. 2532-2540, October, 1970.

1970
A. Hirose, I. Alexeff, W. D. Jones, S. T. Kush, and K. E. Lonngren, "Anomalous Resistivity in a Steady-State, Current-Carrying Discharge- Tube Plasma; Physical Review Letters, Vol. 25, No. 22, pp. 1563-1567, November, 1970.

1970
M. J. Lubin, W. Friedman, M. Roberts, and I. Alexeff, "Plasma Confinement in a High Magnetic Field Toroidal Quadrupole," The Physics of Fluids, Vol. 13, No. 12, pp. 3054-3056, December, 1970.

1970
W. L. Stirling and I. Alexeff, "A Turbulently Heated Electron Plasma," Plasma Physics, Vol. 12, pp. 489-502, Pergamon Press, 1970.

1971
K. Estabrook, I. Alexeff, W. D. Jones and K. E. Lonngren, "Reflection of Pseudowaves," The Physics of Fluids, Vol. 14, No. 1, pp. 185-187, January, 1971.

1971
A. Hirose and I. Alexeff, "Anamalously Rapid Skin-Current Penetration and Heating in Pulsed-Plasma Experiments," Physical Review Letters, Vol. 26, No. 16, pp. 949-952, April, 1971.

1971
M. Widner, I. Alexeff, and W. D. Jones, "Plasma Expansion into a Vacuum," The Physics of Fluids, Vol. 14, No. 4, pp. 795-796, April, 1971.

1971
K. Estabrook, M. Widner, I. Alexeff, and W. D. Jones, "Simulation of Pseudowaves and of Plasma Sheath Formation about a Grid by Computer Solution of the Ion Vlasov Equation," The Physics of Fluids, Vol. 14, No. 8, pp. 1792-1794, August, 1971.

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K. Estabrook, I. Alexeff, "Cherenkov Ion Acoustic Wave Radiation Generated by a Pseudowave," Physics Letters, Vol. 36A, No. 2, pp. 95-96, August, 1971.

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APPENDIX B

Study and Research at the UTK Plasma Science Laboratory

Study and Research at the UTK Plasma Science Laboratory

The Plasma Science Laboratory is affiliated with the University of Tennessee's Electrical and Computer Engineering Department on its Knoxville campus. The city of Knoxville is located among the beautiful hills of East Tennessee, and has recently been designated one of the United States' most livable cities. The UTK Campus serves 25,000 students, and provides the cultural and intellectual stimulation of a major university. Within a hundred mile radius of the campus are recreational opportunities unparalleled in the Eastern United States, including the Smoky Mountain and Big South Fork National Parks; numerous state parks; and many TVA lakes, parks, and recreational areas. These provide opportunities for hiking, backpacking, camping, bicycling, fishing, boating, swimming, white water rafting and canoeing, and contact with wilderness areas.

Research at the UTK Plasma Science Laboratory is supervised by Professors J. Reece Roth and Igor Alexeff, both of whom are Fellows of the Institute of Electrical and Electronics Engineers. The research program is funded by contracts from the Department of Energy, the Air Force Office of Scientific Research, and the Office of Naval Research, which provide approximately $300,000 in support annually.

The UTK Plasma Science Laboratory is unusually well equipped for experimental research in steady-state electric field dominated plasmas, and for studying the absorbtion, emission, and interactions of electromagnetic radiation with such plasmas. The Laboratory has an inventory of over $1.5 million in magnet facilities, power supplies, plasma diagnostic equipment, electronic test instruments, microwave components, and RF sources and network analyzers. A significant proportion of this inventory is state-of-the-art equipment of a kind available in few university or national laboratories.

Major facilities available in the UTK Plasma Science Laboratory include a 20 cm bore, 0.35 Tesla water-cooled magnet system; a 17 cm bore, 0.50 Tesla water-cooled magnet system; a 40k VDC, 1.0 ampere power supply; A LeCroy 3500 SA32 transient recorder system; a three-channel, 10 MHz analog-to-digital data handling system; a 1.0 to 26 GHz Integra Panoramic spectrum analyzer; a Hewlett-Packard Model 8510

microwave network analyzer (45 MHz to 18 GHz); and a Hewlett-Packard Model 3577 low frequency network analyzer (5 Hz to 200 MHz). In addition, the following plasma diagnostic systems are available: A conventional and a mass-analyzed charge-exchange neutral energy analyzer; two ½-meter optical spectrometers; a 1½-meter vacuum ultraviolet spectrometer; a 28 GHz polarization diplexing microwave interferometer; a 28 GHz microwave scattering system; a fluctuation-induced transport diagnostic system, including capacitive and Langmuir probes; a computer-assisted retarding potential energy analyzer system; a computer-assisted Langmuir probe system; mass spectrometers; RF signal generators from 1 Hz to 40 GHz; RF spectrum analyzers from 5 Hz to 18 GHz; calibrated, broadband antennas for RF emission measurements in the range of 0.5-1200 MHz; and many other minor probes and devices.

Major areas of research at the UTK Plasma Science Laboratory include exploratory research on *electric field dominated plasmas; sub-millimeter* microwave devices, including the Orbitron maser; the geometric mean and related interpenetrating beam plasma instabilities; RF emissions and interactions with energetic plasmas; plasma turbulence; anomalous electrical resistivity of electric field dominated plasmas; MHD pumping and power generation using AC; plasma heating by first-order collisional magnetic pumping; and microwave absorbtion resonance spectroscopy of organic and biological materials.

Activities of the UTK Plasma Science Laboratory include contract research; a weekly plasma seminar; experimental research on masters and Ph.D. theses; consulting services by Plasma Lab faculty and staff for local institutions, industry and government; providing state-of-the-art equipment for student training; offering, each summer, the AFOSR - UTK Undergraduate Research Assistantship Program; publishing research results in archival journals; and presenting progress reports on current research at professional society meetings.

The UTK Plasma Science Laboratory is located in Room 101 Ferris Hall and is always available to students for inspection. Part time undergraduate jobs are often available. The Air Force Office of Scientific Research, in cooperation with the Department of Electrical and Computer Engineering, has made available a limited number of undergraduate research assistantships during the summer. These assistantships are for experimental research on AFOSR-sponsored projects. In addition to the above summer undergraduate research assistantship program, graduate research assistantships are available for graduate students interested in pursuing advanced degree work in plasma engineering and fusion energy.

Popularity of the plasma program at UTK is greatest among those students who enjoy building things, and doing hands-on work with actual hardware. Plasma engineering has always appealed to students who wish to do research and development on the leading edge of electrical engineering with technologies that involve the generation and conversion of large amounts of electrical power.

The *Electrical and Computer* Engineering Department at UTK has offered courses in plasma engineering and fusion energy at the graduate and undergraduate levels for more than 15 years. The ECE Department at UTK is one of very few in the country to offer an undergraduate senior option in plasma engineering. Since 1985, the ECE Department has offered, in addition to graduate instruction in plasma engineering, a graduate-level

option in fusion energy in cooperation with the Nuclear Engineering Department.

The plasma and fusion-related courses offered at UTK by the Departments of Electrical and Computer Engineering (ECE), Nuclear Engineering (NE), and Physics and Astronomy (P) are as follows:

Plasma and Fusion-Related Courses at UTK

1. Introductory Plasma Engineering (offered every year)
   ECE 3190 Plasma I-Plasma Engineering (3)
   ECE 4470 Plasma II-Magnetohydrodynamics (3)
   ECE 4480 Plasma III-Kinetic Theory (3)

2. Introduction to Fusion Energy Sequence (offered every year)
   ECE-NE 4445 High Temperature Plasma Physics (3)
   ECE-NE 4455 Principles of Fusion Reactors (3)
   ECE-NE 4465 Introduction to Fusion Technology (3)

3. Weekly Plasma Seminar (offered every quarter)
   ECE 5990 Plasma Science Seminar (1)

4. Plasma Diagnostics Sequence (offered on even-numbered years only)
   ECE-NE 5315 Plasma Diagnostics I (3)
   ECE-NE 5325 Plasma Diagnostics II (3)
   ECE-NE 5335 Plasma Diagnostics Laboratory (3)

5. Intermediate Fusion Energy Sequence (offered on odd-numbered years only)
   NE-ECE 5815 Fundamentals of Fusion Physics and Engineering (3)
   NE-ECE 5825 Plasma Engineering (3)
   NE-ECE 5835 Fusion Technology (3)

6. Advanced Plasma Physics Sequence (offered as demand warrants)
   ECE-P 6500 High Temperature Plasma Physics I (3)
   ECE-P 6510 High Temperature Plasma Physics II (3)
   ECE-P 6520 High Temperature Plasma Physics III (3)

7. Advanced Fusion Energy Sequence (offered as demand warrants)
   NE 6810 Plasma Engineering II (3)
   NE 6820 Fusion Reactor Design (3)
   NE 6830 Special Topics in Fusion Engineering (3)

All the above courses are available for graduate credit; all students in the ECE plasma program or affiliated with the UTK Plasma Science Laboratory are expected to sign up each quarter for ECE-5990, Plasma Science Seminar.

The UTK campus is shifting from a quarter to a semester schedule in the Fall of 1988. The above courses will continue to be offered, but with different (3-digit) catalog numbers and with two rather than three courses in a sequence.

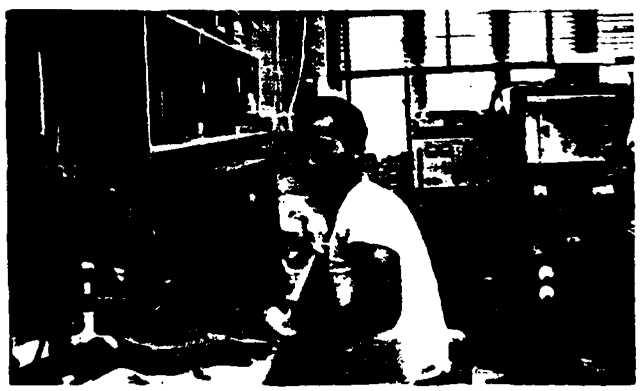
For further information about the UTK Plasma Science Laboratory or the ECE departmental course offerings, please contact

Professor J. Reece Roth
409 Ferris Hall
University of Tennessee
Knoxville, Tennessee 37996-2100
(615) 974-4446

For a graduate catalog and/or application information, please contact

Director, Office of Graduate
Admissions and Records
218 Student Services Building
University of Tennessee
Knoxville, Tennessee 37996-0220
(615) 974-3251

E01-1340-002-87



APPENDIX C

Plasma Science Seminars, 1982-88

5990 EE - PHYSICS PLASMA SEMINAR

Winter Quarter, 1982

Room 405 Ferris Hall
12:00 noon, Fridays

We have asked several outside speakers to come and describe their recent plasma-related work to us. The dates, speakers and approximate topics are as follows:

February 12 - Dr. Owen Eldridge, Fusion Energy Division, ORNL - Current Status of Ion Cyclotron Resonance Heating and recent results from the ORNL EBT-S Experiment.

February 19 - George E. Gorker, Fusion Engineering Design Center, ORNL - Engineering Problems Associated with Handling Large Blocks of Electrical Power for Present and Future Magnetic Fusion Experiments.

February 26 - Philip T. Spampinato, Fusion Engineering Design Center, ORNL - Reference Design and Current Status of the Fusion Engineering Device (FED).

March 5 - Philip Ryan, Fusion Energy Division, ORNL - Status report on his Ph.D. thesis in EE, on the subject of neutral beam development for plasma heating.

Students, faculty and staff are welcome to attend.

5990 EE - PHYSICS PLASMA SEMINAR

Spring Quarter, 1982

Room 405 Ferris Hall
12:00 noon, Fridays

We have asked several outside speakers to come and describe their recent plasma-related work to us. The dates, speakers and approximate topics are as follows:

April 16 -- J. Rand McNally, Jr., Fusion Energy Division, ORNL (retired) The physics of advanced fuel fusion.

May 7 -- Prof. Edward G. Harris, Department of Physics, UTK Catastrophe theory as applied to the ELMO Bumpy Torus and other plasmas.

May 28 -- Dr. Vishnu Srivastava, Fusion Engineering Design Center, ORNL. Superconducting magnet technology in the Fusion Engineering Device (FED).

Students, faculty, and staff are welcome to attend.

PH 5990

Plasma Seminar Schedule Fall 1983

Room 504 Ferris Hall
12:00 Noon, Wednesdays

DATE	SPEAKER AND TOPIC
Sept. 28 -	Prof. Igor Alexeff - Beam-Plasma Instabilities
Oct. 5 -	Mr. Paul Spence - Broadband Antennas
Oct. 12 -	Prof. J. Reece Roth - Scaling Laws for Fusion Reactors
Oct. 14 -	Prof. D Rosenberg - Network Analyzers
Oct. 26 -	Prof. Igor Alexeff - Recent Results in Orbitron Research
Nov. 2 -	Dress Rehearsals for the APS Plasma Physics Divison Meeting
Nov. 9 -	No Plasma Seminar
Nov. 16 -	Trip Report on APS Plasma Physics Division Meeting
Nov. 23 -	Dr. Owen Eldridge, ORNL - Electron Cyclotron Plasma Heating
Nov. 30 -	Mr. Peyman Dehkordi - Operation of the Analog-to-Digital Data Handling System.

All interested persons are invited to attend.

For further information contact

Prof. J. Reece Roth
Dept. of Electrical Engineering
(615) 974-4446

UTK PLASMA SCIENCE SEMINAR SERIES

FALL, 1984

Wednesdays, 9:00 AM 504 Ferris Hall

DATE	
September 26	Profs. Alexeff and Roth, Trip Report on the International Conference on Plasma Physics, Lausanne, Switzerland
October 3	Prof. I. Alexeff, "Recent Progress with the Orbitron Maser"
October 10	Ms. Lisa Hood and Mr. John Clark, UTK Office Of public Relations, "How to Deal with Reporters"
October 17	Prof. J. R. Roth, "Recent Progress with Two Beam Interaction Instabilities"
October 24	Dress Rehearsals for the APS Plasma Physics Division Annual Meeting
October 31	NO SEMINAR - APS MEETING WEEK
November 7	Prof. J. R. Roth, "Plasma Etching for Microelectronics", based on materials provided by J. W. Coburn, IBM
November 14	Mr. William Casson, ORNL, "Far Infrared Scattering on EBT"
November 21	Mr. Phillip Spampinato, Fusion Engineering Design Center, ORNL "Robotics in Fusion Research"
November 28	Prof. J. R. Roth, "How to Get Government Research Contracts"
December 5	Topic to be arranged.

WINTER QUARTER 1985

PLASMA SCIENCE SEMINAR SERIES

Room 504 Ferris Hall
Tuesdays, 9:00-10:15 am

DATE	SPEAKER AND TOPIC
January 15	J. Reece Roth, "How to Obtain Surplus Government Equipment for Experimental Research"
January 24 THURSDAY	Dr. Robert J. Barker, AFOSR, Bolling AFB, Washington, D.C., "Two-and Three-Dimensional Particle-in-Cell Electromagnetic Plasma Simulation".
January 29	Prof. Igor Alexeff, "Recent Results in Orbitron Research"
February 5	Prof. J. Reece Roth, "Plasma Etching fo Microelectronics-II", Based on notes and vue-graphs supplied by J. W. Coburn of IBM.
February 12	Prof. David Rosenberg and Mr. Paul D. Spence, "RF Plasma Emissions Measured with Calibrated, Broadband Antenna".
February 19	Mr. Antonino Carnevali, Fusion Energy Division, ORNL,"Confinement of Beam Ions in the ISX-B Plasma". This willl be a report on Mr. Carnevali's Ph.D. thesis in the Physics Department
February 26	Dr. Michael J. Gouge, DoE Program Office, Oak Ridge, "Alpha-Driven Currents in Tokamak Reactors". Dr. Gouge will present his recently-completed Ph.D. thesis for the UTK Physics Department.
March 5	Mr. Wlodzimierz (Vlodek) Nakonieczny, "Particle Orbits in the Orbitron Microwave Emitter". This will be a progress report on a Ph.D. Thesis.
March 12	Mr. Mounir Laroussi, "Progress in Theoretical Understanding of Transit-Time Magnetic Pumping and Collisional Plasma Heating".

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

SPRING QUARTER 1985

PLASMA SCIENCE SEMINAR SERIES

Room 504 Ferris Hall
Thursdays, 9:00-10:15 am

DATE	SPEAKER AND TOPIC
April 4	Mr. Gregory Hutchens, University of Illinois, "Group Invariance Properties of the Grad-Shafranov Equation". Mr. Hutchens is a graduate of the UTK Engineering Physics program now studying at Illinois in their Nuclear Engineering Program.
April 11	Prof. Igor Alexeff, "Recent Results from the Orbitron Microwave Emitter at Submillimeter Wavelengths".
April 18	Profs. J. Reece Roth and David Rosenberg, UTK, and Dr. Howard Adler, ORNL, "Interaction of Electromagnetic Radiation with Biological Samples" Joint meeting with the Department of Microbiology and other interested persons to explore research opportunities in this area.
April 25	Mr. Paul Spence, "Measurement of RF Plasma Emissions with Calibrated Antennas", A progress report on Mr. Spence's research program in the UTK Plasma Science Laboratory.
May 2	W. Don Nelson, ORNL Fusion Engineering Design Center, "The Fusion Power Demonstration Study".
May 9	Mr. Fred Dyer, Experimental Technique Associated with Orbitron Microwave Emitters"
May 16	Mr. Mounir Laroussi, "Recent Theoretical Progress on Collisional and Transit-Time Plasma Heating", A progress report on Mr. Laroussi's Ph.D. research program.
May 23	Mr. G. Reza Ghayspoor, "Progress in the Development of a VAX-Assisted Data Handling and Reduction System for Plasma Measurements", A progress report on Mr. Ghayspoor's M.S. thesis research.
May. 30	Dress Rehearsals for poster papers at the IEEE International Conference on Plasma Science, Pittsburgh, PA, June 3-5, 1985.

FALL QUARTER 1985-1986

PLASMA SCIENCE SEMINAR SERIES

EE 5990 - - Section 34482

Room 504 Ferris Hall

Thursdays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
October 3	Prof. Igor Alexeff, A Plasma Wave Oscillator.
October 10	Prof. J. Reece Roth, The Impact of Plasma Heating Efficiency on the Power Balance of Powerplant Fusion Reactors. This is a dress rehearsal for an invited talk and conference paper.
October 17	Paul Spence, Operation of the HP Microwave Network Analyzer, Followed by a hands-on workshop with the instrument in the UTK Plasma Science Laboratory.
October 24	G. Reza Ghayspoor, Development of an Integrated Data Acquisition and Handling System for the Measurement of Radial Transport Rates, Based on Digital Time Series Analysis. This is a M.S.E.E. thesis summary.
October 31	Dress rehearsals of papers for APS Plasma Meeting.
November 7	NO SEMINAR - APS MEETING WEEK
November 14	F. William Wiffen, Metals and Ceramics Division, and Fusion Engineering Design Center, ORNL; Materials Problems and Potential Solutions in Fusion Reactors.
November 21	David Coffey, President, The Nucleus, Inc., How to Start Your Own Small Business.
December 5	John E. Crowley, Low-Noise Measurements of Plasma Turbulence.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

PLASMA SCIENCE SEMINAR SERIES

EE 5990--Section 32437
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
January 10	Prof. Igor Alexeff, Department of Electrical Engineering UTK, "Trip Report on the Infrared and Millimeter Wave Conference". This IEEE cosponsored conference was held in December, and many new advances were reported.
January 17	Prof. Karl Audenaerde, Chairman, Engineering Department, State University of New York at New Platz,"Microwave Mode Convertors".
January 24	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Transit Time Effects on the Divergence Term of the Plasma Continuity Equations".
January 31	Mr. John E. Crowley, GRA, UTK Plasma Science Laboratory, Low-Noise Measurements for Plasma Turbulence Research". This status report will cover Mr. Crowley's Master's thesis research in the UTK Plasma Lab.
February 7	Mr. G. Reza Ghayspoor, GRA, UTK Plasma Science Laboratory, "Extension of the LeCroy Transient Recorder System to Three Simultaneous Channels". This is an updating of Mr. Ghayspoor's recent Master's degree.
February 14	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory, "First-Order Plasma Heating Using Collisional Magnetic Pumping". This status report will describe the theoretical aspects of Mr. Laroussi's Ph.D. thesis.
February 21	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "How to Write a Textbook". Useful hints on writing a textbook in the word-processor era and some interesting aspects of the book publishing business will be discussed.
February 28	Prof. Marshall Pace, Department of Electrical Engineering, UTK, "Research at UTK on the Initiation of Dielectric Breakdown". Prof. Pace will describe some research underway at UTK in this area.
March 7	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Theoretical and Experimental aspects of the Plasma Continuity Equation Oscillation". This will describe a plasma instability first discovered experimentally and described theoretically by Prof. Roth.
March 14	Dr. Robert W. Schumacher, Hughes Research Laboratories, Malibu, California, "Microwave Tube Research at the Hughes Research Laboratories". Dr. Schumacher will discuss the Hughes research program in this area, including their work on the Orbitron maser.

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WINTER QUARTER, 1986

PLASMA SCIENCE SEMINAR SERIES

Spring, 1986

EE 5990--Section 33236
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 pm

Date	SPEAKER AND TOPIC
April 4	Organization meeting and dress rehearsals for the 1986 SSST Plasma Papers
April 11	Prof. Igor Alexeff, Department of Electrical Engineering, UTK "Recent Progress in Orbitron Research".
April 18	Mr. John B. Miller, Fusion Engineering Design Center, ORNL, "Prevention of the Current-Quench Phase of a Major Disruption in a Tokamak Reactor" This plasma engineering study is Mr. Miller's Ph.D. Thesis in Nuclear Engineering.
April 25	Mr. Tim Bigelow, Fusion Energy Division, ORNL, "A Survey of Plasma RF Heating Experiments in Japan". A report of his recent trip to Japanese Fusion Labs.
May 2	Profs. J. Reece Roth and Igor Alexeff, Dept. of Electrical Engineering, UTK. "A Study of Tokamak Confinement Time Scaling Based on MHD Current Penetration". A derivation of an alcator-like confinement time scaling from first principles.
May 9	Mr. John E. Crowley, GRA, UTK Plasma Science Laboratory, "Conversion of the HP 3577A Network Analyzer to a Low Noise Spectrum Analyzer Mode of Operation". This seminar will double as Mr. Crowley's oral exam on his M.S. Thesis.
May 16	Mr. Phil Ryan, Fusion Energy Division, ORNL, and UTK Ph.D. candidate, "Analysis and Design of an Energy Recovery System for a Space Charge Neutralized Ion Beam". A summary of Mr. Ryan's Ph.D. Thesis.
May 23	Prof. J. Reece Roth, Department of Electrical Engineering, UTK, "Trip Report on the 13th IEEE International Conference on Plasma Science, Sakatoon, Canada," and "Langevin Formalism for Absorbtion of RF Power at Gyroresonance"
May 30	Mr. Paul Spence, GRA, UTK Plasma Science Laboratory, "Measuring Collision Frequencies by Microwave Absorbtion"

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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PLASMA SCIENCE SEMINAR SERIES

Fall Quarter, 1986

ECE 5990--Section 34067
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
September 26	ORGANIZATION MEETING - Prof. J. Reece Roth, UTK: "Trip Report on the Gordon Conference on Plasma Chemistry"; and Prof. Igor Alexeff, UTK: "Survey of Off-Campus Orbitron Research"
October 3	Prof. Igor Alexeff, ECE Dept., UTK: "Recent Progress on Orbitron and MHD Research at UTK".
October 10	Mr. John E. Crowley, GRA, UTK Plasma Science Laboratory: "Experimental Performance of the HP 3577A Two-Channel Conversion System".
October 17	Prof. J. Reece Roth, ECE Dept., UTK: "Research Opportunities in the Interaction of Electromagnetic Radiation with Biological Samples".
October 24	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory: "Computer Simulation of Plasma Heating by Collisional Magnetic Pumping".
October 31	Dress rehearsals for the APS meeting.
November 7	No seminar this week - APS Plasma Physics Division Meeting in Baltimore, MD.
November 14	Mr. Paul Spence, GRA, UTK Plasma Science Laboratory: "Recent Results of Experimental Turbulence Research".
November 21	Mr. Alan L. Wintenberg, GRA, UTK ECE Department: "Pre-Breakdown Studies in Liquid Dielectrics".
December 5	Mr. Mark Rader, GRA, UTK Plasma Science Laboratory: "Recent Progress on the Steady-State Orbitron Microwave Emitter".

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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PLASMA SCIENCE SEMINAR SERIES

Winter Quarter, 1987

ECE 5990--Section 32423
Room 504 Ferris Hall
Fridays, 1:00 to 2:15 p.m.

DATE	SPEAKER AND TOPIC
January 9	Prof. J. Reece Roth, UTK: "Recent Developments in Aneutronic Fusion for DoD Space Power and Propulsion Systems." A scout report from Washington on recent DoD interest in fusion energy.
January 16	Mr. Gregory Hutchens, Univ. of Illinois: "Nuclear Reactor Kinetics and Fusion Reactors" Mr. Hutchens is a former student, B.S. in Engineering Physics, who will report on his doctoral research at Illinois.
January 23	Prof. Igor Alexeff, UTK: "How to Start Your Own Company: Innovation and Venture Capital" Prof. Alexeff will draw on his experiences as founder and first President of the Tennessee Inventor's Association.
January 30	Prof. J. Reece Roth, UTK: "Theory of Plasma Ion Implantation for Hardening Metals". This will describe the plasma conditions required to achieve a given level of ion implantation in complex metal objects, and how to calculate exposure times, energy requirements, and other commercially significant factors in the application of this new process.
February 6	Prof. Igor Alexeff, UTK: "A New Theory of Dielectric Breakdown in Liquids". This will discuss a new theory developed from experimental data taken in Prof. Marshall Pace's Laboratory.
February 13	Paul N. Haubenreich, Fusion Energy Division ORNL: "Superconducting Magnets for Fusion Confinement", A survey of superconducting magnet technology and a progress report on ORNL's impressive Large Coil Program.
February 20	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory: "Theoretical and Computational Results for Collisional Magnetic Pumping". This will summarize the theoretical portion of Mr. Laroussi's Ph.D. Thesis, and contain a progress report on his experimental research.
February 27	Dr. Joseph C. Danko, Director, UTK Center for Materials Processing: "Plasma Processing of Materials". Prof. Danko will discuss some large-scale commercial applications of plasmas and some promising new plasma-based materials processing methods.
March 6	David W. Swain, Fusion Energy Division, ORNL: "Research and Development on Radio Frequency Power at ORNL". A survey of high power RF technology and applications at ORNL.
March 13	Prof. Igor Alexeff, UTK; and Mr. Mark Rader, GRA, UTK Plasma Science Laboratory: "Recent Advances in Orbitron Development and in Microwave Technique". This will summarize interesting recent developments in these areas.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

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PLASMA SCIENCE SEMINAR SERIES

Spring Quarter, 1987

ECE 5990--Section 31628
Room 504 Ferris Hall
Fridays, 12:00 to 1:15 p.m.

DATE	SPEAKER AND TOPIC
April 3	Mr. Ali Keshavarzei, Senior, ECE Department, UTK: "Low Frequency Continuity-Equation Oscillations In Partially Ionized Gases". This will be a dress rehearsal for Mr. Keshavarzi's appearance in the final round of the Region III IEEE Student Paper Competition at Southeastcon '87 in Tampa.
April 10	Prof. J. Reece Roth, UTK ECE Department: "How to write Architect's Guidelines for Scientific Research Workspace". This is something that nearly everyone does once or twice in their careers, and may be useful to some in connection with the future Science/Engineering/Computer (SEC) Research Building.
April 24	Mr. John C. Mannone, UTK Department of Physics and Astronomy: "Modeling of Electron Transport in Dielectric Fluids Subject to High Electric Fields". This will consist of a report on an electrohydrodynamic (EHD) experiment performed in the UTK Plasma Science Laboratory.
May 1	Prof. Igor Alexeff, UTK ECE Department: Advances in High Voltage Beakdown in Liquids". This will summarize theoretical progress made in joint collaboration with Prof. Marshall Pace's research group.
May 8	Mr. Mark Rader, GRA, UTK Plasma Science Laboratory, "How to Use the Presentation Graphics Package on the Plasma Lab's HP 9836 Computer".
May 15	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory, "Recent Results from Experiments with the Collisional Magnetic Heating of Plasmas". This will describe recent research results and also contain a trip report on the APS Topical Meeting on the RF Heating of Plasmas.
May 22	Prof. J. Reece Roth, UTK ECE Department: "How to Organize a Technical Conference". This is something that one gets stuck with sooner or later, so you might find it useful to know what mistakes to avoid.
May 29	Mr. Paul D. Spence, GRA, UTK Plasma Science Laboratory, "Recent Results from Experiments wth Plasma Turbulence". A progress report on Paul's Ph.D. thesis, now in its final stages.

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PLASMA SCIENCE SEMINAR SERIES

Fall Quarter, 1987

ECE 5990--Section 33945
Room 504 Ferris Hall
Fridays, 12:00 to 1:00 p.m.

DATE	SPEAKER AND TOPIC
September 26	Organization Meeting - Prof. J. Reece Roth, UTK: "Trip Report on the 18th International Conference on Phenomena in Ionized Gases, Swansea, Wales". Slides and a summary of recent advances.
October 2	Prof. Igor Alexeff, UTK: "Trip Report on the International Conference on High Power Microwave Sources, Chengdu, China." Slides of the conference and the fusion research institute.
October 9	Prof. J. Reece Roth, UTK: "Space Applications of Fusion Energy." Preview of a paper at the 12th Symposium on Fusion Engineering.
October 16	Prof. Alexeff, UTK: "Advanced Orbitron Developments." Recent results of orbitron Research in the UTK Plasma Science Laboratory.
October 23	Mr. Tom E. Shannon, Manager, Fusion Engineering Design Center, ORNL: "Status of the Compact Ignition Tokamak (CIT) Project." This talk will describe the proposed step in DT Tokamak Research beyond the TFTR experiment.
October 30	Prof. Igor Alexeff and J. Reece Roth, UTK; and Mr. Fred Dyer, Mark Rader, Paul Spence and Mounir Laroussi, GRAs, UTK Plasma Science Laboratory: "Dress Rehearsal for APS Annual Meeting of the Plasma Physics Division." An overview and progress report on recent work done in the plasma lab.
November 6	APS Plasma Physics Division - No seminar this week
November 13	Prof. J. Reece Roth, UTK: "Trip Report on the 8th International Conference on Plasma Chemistry, Tokyo, Japan." Report on recent advances in plasma-assisted diamond deposition, thermal plasmas, and plasma torches, with slides of the conference, plasma equipment exhibitors, and major Japanese fusion facilities.
November 20	Dr. Antonino Carnevalli, RPI and Fusion Energy Division, ORNL: "Heavy Ion Beam Probing - Measurement of Plasma Potential and Turbulent Transport." Dr. Carnevalli is a former UTK student who is now working on the ATF Experiment at ORNL.
November 27	Thanksgiving Holiday
December 4	Mr. Scott Stafford and Mr. Min Wu, GRAs, UTK Plasma Science Laboratory. "Proposed Masters Thesis Research."

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PLASMA SCIENCE SEMINAR SERIES

Winter Quarter, 1988

ECE 5990--Section 33743

Room 504 Ferris Hall

Fridays, 12:05 to 12:55 p.m.

DATE	SPEAKER AND TOPIC
January 8	UTK closed due to bad weather
January 15	Organization meeting, including viewing of a 20-minute video tape, "Nuclear Engineering and Plasma Physics Research at the University of Washington, Seattle".
January 22	Prof. Igor Alexeff, ECE Dept., UTK, "Trip Report on the Conference on Infrared and Millimeter Waves". Many interesting recent advances were reported at this meeting, including our own Orbitron work.
January 29	Prof. J. Reece Roth, ECE Dept., UTK, "Recent Developments in the Treatment of Heart Disease", The only warning that half the victims of heart disease have is death. Prof. Roth will present a layman's summary of recent developments in risk factors, methods of treatment, and thresholds for action.
February 5	Mr. Frank Davis, ORNL, "Remote Maintenance of the Compact Ignition Torus (CIT)". Mr. Davis is responsible for developing the robotic manipulators used to deal with radio-activated components from this fusion reactor.
February 12	Prof. Mark Kot, UTK Mathematics Dept., "Routes to Chaos". This will be a tutorial on the development of chaotic behavior from deterministic, nonlinear systems such as plasma turbulence.
February 19	Mr. Mounir Laroussi, UTK Plasma Science Laboratory, "Recent Experimental Results from Collisional Magnetic Pumping Research", A semifinal report on Mounir's Ph.D. thesis research.
February 26	Mr. Paul D. Spence, UTK Plasma Science Laboratory, "Research on Plasma Instabilities and Turbulence", A semi-final report on Paul's Ph.D. thesis research.
March 4	Mr. Scott Stafford and Mr. Min Wu, UTK Plasma Science Laboratory, "Progress Reports on Master's thesis research in the UTK Plasma Science Laboratory"

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PLASMA SCIENCE SEMINAR SERIES

Spring Quarter, 1988

ECE 5990--Section 33127
Room 504 Ferris Hall
Fridays, 12:05 to 1:00 p.m.

DATE	SPEAKER AND TOPIC
March 5	Organization Meeting. Also, Prof. J. Reece Roth, UTK, "Survey of Plasma Science". This talk will cover the many engineering and industrial applications of Plasma Physics. An extensive topical outline will be distributed.
April 1	No Seminar - University Holiday
April 8	Prof. Igor Alexeff, UTK, "Recent Developments in the Orbitron MASER". This will be a dress rehearsal of Prof. Alexeff's invited paper at the IEEE Southeastcon '88 meeting.
April 15	Mr. Alan Wintenberg, GRA, UTK Department of Electrical and Computer Engineering, "Recent Research in Liquid Dielectrics at UTK". This is a progress report on some interesting discoveries recently made at UTK on pre-breakdown phenomena.
April 22	Dr. James F. Lyon, ORNL Fusion Energy Division: "The ORNL Advanced Toroidal Facility (ATF) and Its Relation to the World Stellarator Program" this will include a description and preliminary results from ORNL's newest fusion experiment.
April 29	Prof. Mark Kot, UTK Department of Mathematics, "Routes to Chaos - II". This will be a continuation of Prof. Kot's lecture last quarter on the theory of chaos as it may apply to plasmas.
May 6	Dr. Michael J. Gouge, ORNL Fusion Energy Division, "Pellet Injection for Fusion-Related Plasmas". This talk will describe the outstanding work at ORNL on refueling fusion plasmas by accelerating pellets of hydrogen ice to speeds faster than a bullet.
May 13	Prof. J. Reece Roth, UTK, "Recent Developments in Plasma Chemistry and in Mining ^{3}He from the Lunar Surface". This talk will summarize two recent workshops on these very different subjects.
May 20	Mr. Mounir Laroussi, GRA, UTK Plasma Science Laboratory, "Plasma Heating by Collisional Magnetic Pumping". This will be a final report on the theoretical and experimental aspects of Mounir's Ph.D. thesis.
May 27	Mr. Mark S. Rader GRA, UTK Plasma Science Laboratory, "Development of the First Steady-State Orbitron". This will be a presentation of Mark's Masters Thesis research.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

PLASMA SCIENCE SEMINAR SERIES

Fall Semester, 1988

ECE 495--Section 33252
ECE 598--Section 33430

Room 504 Ferris Hall
Fridays, 12:20 to 1:10 p.m.

DATE	SPEAKER AND TOPIC
August 26	ORGANIZATION MEETING - Prof. J. Reece Roth, UTK: "A Survey of Plasma Science" This lecture will review some of the industrial uses of this rapidly developing field, and show slides of some industrial exhibitors at a recent international conference on plasma chemistry.
September 2	Prof. J. Reece Roth, UTK: "Mysteries of Plasma Physics: Part I-Ball Lightning". This lecture is the first in a series designed to explore some classic unsolved problems in plasma physics. Some physical mechanisms for ball lightning will be explored in light of available observations, and their possible relevance to weapons and fusion energy will be discussed
September 9	Prof. Igor Alexeff, UTK: "Recent Progress on the Orbitron Submillimeter Microwave Maser and on Related Devices". Prof. Alexeff, who holds the basic patent on the Orbitron tube, will describe some recent advances made in the UTK Plasma Science Laboratory.
September 16	Prof. J. Reece Roth, UTK: "How and Where to Publish Scientific Papers". This talk will review the procedure followed to organize, write, and publish scientific papers in the archival literature. New information on the relative cost of publication and readership of various plasma journals will be presented.
September 23	Prof. Igor Alexeff, UTK: "Trip Report on Recent Microwave Tube Conferences". Prof. Alexeff will report on some exciting new developments in the subjects of high frequency and high power microwave power production.
September 30	Prof. J. Reece Roth, UTK: "Mysteries of Plasma Physics: Part II - Confinement Time Scaling in Tokamaks". This lecture is the second in a series on classic unsolved problems in plasma physics. After 35 years of fusion research, the mechanism by which particles get from the inside to the outside of tokamaks has not yet been identified. Some phenomenological scaling laws, unsuccessful theories, and possible models will be discussed.
October 7	Prof. J. Reece Roth, UTK: "Space Applications of Fusion Energy". This will be a dress rehearsal for the 8th ANS Topical Meeting on the Technology of Fusion Energy, October 9-13, 1988.

October 14	Mr. Scott Painter, ORNL: "Alpha Particle Losses from Compact Torsatrons". This talk will be a progress report on Mr. Painter's Ph.D. thesis for the UTK Nuclear Engineering Department.
October 21	Mr. Min Wu, GRA, UTK Plasma Science Laboratory: "Experimental Research on Plasma Heating by Collisional Magnetic Pumping". This will be a report on Mr. Wu's Master's thesis.
October 28	Dress rehearsal of papers for the APS Plasma Physics Division Meeting.
November 4	No meeting this week-APS Plasma conference.
November 11	Profs. Igor Alexeff and Marshall Pace, and Mr. Alan Wintenberg, UTK: "Recent Progress in Understanding Electrical Breakdown in Dielectric Fluids". This will describe research done under a DoE contract here in Ferris Hall.
November 18	Mr. Scott Stafford, GRA, UTK Plasma Science Laboratory: "Application of Chaos Theory to Experimental Plasma Turbulence". This will be a report on Mr. Stafford's Master's thesis
December 2	Mr. Thomas E. Shannon, ORNL: "Design and Cost Evaluation of a Generic Magnetic Fusion Reactor Using the DD Fuel Cycle". This talk will outline the highpoints of Mr. Shannon's Ph.D. thesis for the Engineering Science and Mechanics Department at UTK.

ALL INTERESTED PERSONS ARE INVITED TO ATTEND

For further information, contact J. Reece Roth, 974-4446

PLASMA SCIENCE SEMINAR SERIES

SPRING SEMESTER, 1989

Room 510 Ferris Hall
Fridays, 12:20 to 1:10 p.m.

All Interested Persons are Invited to Attend
For further information, contact Prof. J. Reece Roth, 974-4446

DATE	SPEAKER AND TOPIC
January 13	ORGANIZATIONAL MEETING - Course requirements and schedule will be reviewed. Prof. J. Reece Roth, UTK: "Ball Lightning as a Route to Fusion Energy". This is a dress rehearsal for a January 17 seminar at the ORNL Fusion Engineering Design Center on why the observed characteristics of ball lightning are of fusion interest.
January 20	Prof. Igor Alexeff, UTK: "A Visible Plasma". Prof. Alexeff will discuss original research on cesium at the UTK Plasma Science Laboratory, which exhibits cesium's electron plasma frequency in the visible part of the electromagnetic spectrum.
January 27	Prof. Thomas T. Meek, UTK Dept. of Materials Science and Engineering: "Microwave Processing of Ceramics and Other Dielectric Materials". This will describe a new method to rapidly shorten the processing times and improve the characteristics of dielectric materials using a plasma-related method.
February 3	Prof. J. Reece Roth, UTK: "How to Write a Textbook". Sometime during one's career, writing a textbook may become appropriate. Hints on how to organize the task, negotiate with publishers, and handle mechanical details will be presented.
February 10	Mr. Mark Rader, GRA, UTK Plasma Science Laboratory: "A Correction to Landau's Theory of Plasma Damping". This lecture will describe work which evolved from a careful re-examination of the literature.
February 17	Dr. Richard J. Colchin, ORNL Fusion Energy Division: "Electron Beam and Magnetic Field Alignment Experiments in Magnetic Containment Configurations". In magnetic fusion experiments, particles cannot be confined for the necessary second or so unless perturbations of the magnetic field are benign. Dr. Colchin will describe the measurement and reduction of perturbations which lead to plasma loss.
February 24	Prof. J. Reece Roth, UTK: Mysteries of Plasma Physics, Part III - "Moving Striations". Moving striations, which are sometimes visible as moving blobs of luminous plasma in faulty fluorescent light tubes, were first observed by Michael Faraday in the 1830's. To date, there is no generally accepted theory of their operation, making this one of the oldest unsolved problems in plasma physics.

March 3	Prof. J. Reece Roth, UTK: Mysteries of Plasma Physics, Part IV - "Pulsar and Pulsar RF Emission Mechanisms". As pulsar periods approach one millisecond, models based on a rotating neutron star become less tenable because of centrifugal forces. An alternative plasma-based model for millisecond and sub-millisecond pulsars will be presented.
March 10	Mr. Scott A. Stafford, GRA, UTK Plasma Science Laboratory: "Application of Chaos Theory to Fluctuations in a Turbulent Plasma". This talk will describe an experimental masters thesis performed in the plasma lab, in which chaos theory is used to characterize plasma fluctuations, using a commercial software program.
March 17	Mr. Philip F. Keebler and Mr. Min Wu, GRAs, UTK Plasma Science Laboratory; and Mr. In-Seop Lee, GRA, MS&E Department, UTK: "Status of Plasma Ion Implantation Experiments at UTK." This talk will describe the apparatus, methods, and preliminary results of plasma ion implantation experiments designed to improve the corrosion and wear resistance of metals using a new plasma-related technique.
March 31	Mr. J. G. Delene, ORNL Engineering Technology Division: "An Economic Study of Fusion Energy". ORNL has recently participated in a major study which has indicated the plasma-physical and engineering constraints that will make fusion energy economically competitive with other energy sources.
April 7	Mr. Li Li Jiang, GRA, UTK Plasma Science Laboratory: "Recent Research on the Interaction of Microwave Radiation with Magnetized Plasmas". This will report progress on plasma cloaking, an AFOSR-sponsored research effort to explore the feasibility of making targets disappear from radar screens by absorbing radar pulses in a magnetized plasma.
April 14	Mr. Scott L. Painter, ORNL Fusion Energy Division: "A Progress Report on the Design of Compact Torsatrons". This will describe Mr. Painter's Ph.D. thesis, which is concerned with the engineering design of fusion reactors based on ORNL's ATF magnetic containment configuration.
April 21	Prof. Marshall O. Pace and Dr. Alan L. Wintenberg, ECE Department, UTK: "Fast Photography and Current Measurements of Prebreakdown Activity in Insulating Fluids". This experimental work, done in Ferris Hall, has yielded new insights into the physical processes responsible for arcing and breakdown in insulating fluids.
April 28	Dr. Masanori Murakami, ORNL Fusion Energy Division: "Recent Results from the ATF Torsatron at ORNL". The behavior and characteristics of Oak Ridge's newest fusion experiment will be discussed.

APPENDIX D

Bibliography of Archival Publications Supported by Contract AFOSR 86-0100

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APPENDIX D

BIBLIOGRAPHY OF ARCHIVAL PUBLICATIONS SUPPORTED BY CONTRACT AFOSR 86-0100

Publications **Page**

Publications Page

APPENDIX E

Text of Archival Papers Supported by Contract AFOSR 86-0100

ISSN 0094-2898

PROCEEDINGS

THE EIGHTEENTH SOUTHEASTERN SYMPOSIUM ON SYSTEM THEORY

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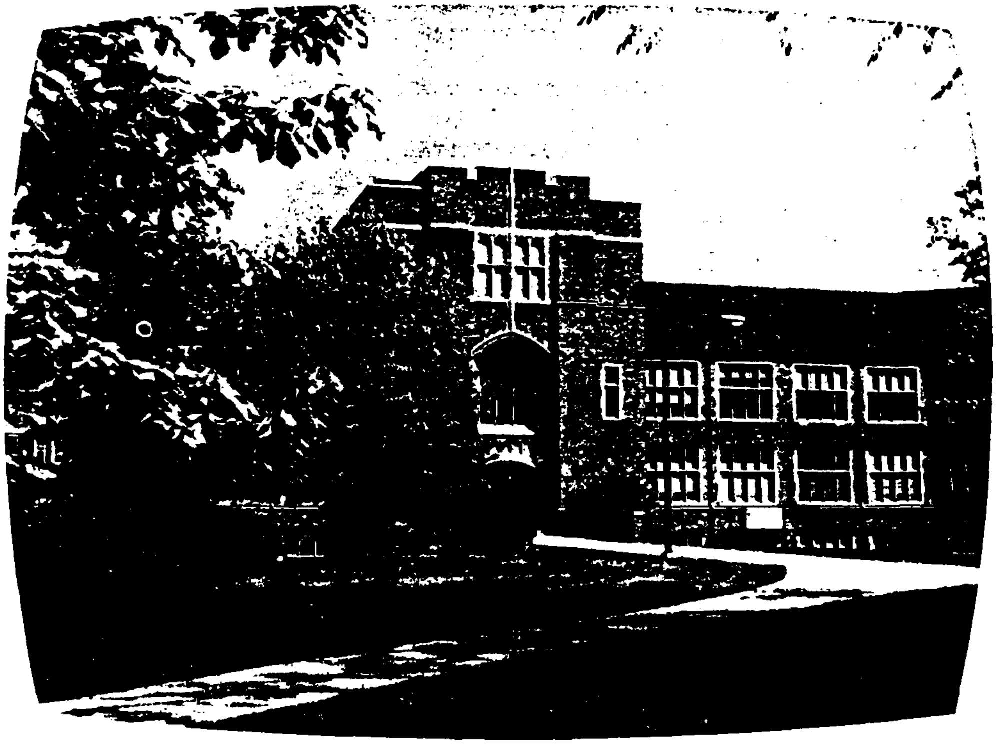

THE UNIVERSITY OF TENNESSEE/KNOXVILLE, TENNESSEE APRIL 7-8, 1986

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PLASMA HEATING BY COLLISIONAL MAGNETIC PUMPING

Mounir Laroussi

Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

ABSTRACT

In controlled fusion research, it is necessary to heat plasma to kinetic temperatures of at least 10 Kev. Collisional magnetic pumping[1-3] is a potentially effective heating method which has not received much attention to date. In this paper, Floquet theory is used to solve the second order differential equation which describes the plasma heating process. The classical result with a heating rate of second order in the magnetic perturbation is obtained. Another form of magnetic perturbation is then assumed, in which first order heating is possible. A heating rate several hundred times larger than the classical one can thus be achieved.

INTRODUCTION

Collisional magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_o (1 + \delta f(t))$, where f(t) is a bounded periodic function with a frequency below the ion cyclotron frequency. The change in the energy of the particles is governed by an homogeneous linear differential equation of the second order with periodic coefficients. Examples of such equations are Mathieu's equation and Hill's equation, which appear in astronomical and other applications where the stability of periodic systems is at issue. The general solutions of these equations have been given by Floquet[4]. The form of the solution is given by:

$$F(t) = a_1 e^{\mu_1 t} \phi_1(t) + a_2 e^{\mu_2 t} \phi_2(t).$$

The parameters μ_1 and μ_2 are called the characteristic exponents. They are calculated from the characteristic equation associated with the differential equation. $\phi_1(t)$ and $\phi_2(t)$ are periodic functions with a period equal to that of the coefficients of the differential equation. In our application, Floquet's theory, along with a perturbation treatment, has been used to calculate the rate of energy increase of plasma contained in a periodically perturbed magnetic field. First a sinusoidal perturbation of the magnetic field has been assumed[5]. In this case, the rate of energy increase has been found to be proportional to the square of the field modulation factor defined by $\delta = \Delta B/B_0$. The parameter δ is a small number, so δ^2 is even smaller, and consequently the plasma heating rate is relatively small. A dependence on the first order of δ was sought. For that, a general perturbation f(t) has been assumed and a condition for first order dependence has been achieved by solving the differential equation using Floquet's theory and a perturbation treatment. (The case where a general form of the magnetic perturbation is assumed and a condition for first order heating is reached will be published in a later work.) As a specific application, a sawtooth perturbation function has been assumed. This results in a plasma heating rate dependent on the first power of δ. It improves the heating rate by two to three orders of magnitude. It is also to be noted that the collision frequency of the plasma is of great importance. In the plasma studied in the UTK Plasma Science Laboratory violent turbulence is present, yielding a high collision frequency which enhances the energy transfer, and the plasma heating rate.

SOLUTION TO THE SINUSOIDAL PERTURBATION

In the first section of this paper we are going to consider the case where the function f(t) is equal to cos ωt, which gives a sinusoidal perturbation . The magnetic field assumes the following form:

$$B = B_o(1 + \delta \cos \omega t) \tag{1}$$

where $\delta << 1$, so that the external oscillator provides a small perturbation on the original static magnetic field. At time t = o, the magnetic field under the coil is slightly stronger than its background value B_o, and half a period later, the magnetic field is weaker than the background value by the same amount. In order to have collisional heating, the transit time of the particles through the heating region has to be longer than the collision time, and both times should be much larger than the cyclotron period. Also the period of oscillation of the magnetic field is comparable to the collision time. These conditions can be written as follows

$$\tau_{ci} << \tau coll \sim \tau_f << \tau_{tr},$$

or

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$$\frac{V_i}{L} << v_c \sim \omega << \omega_{ci}$$

It is known that when the magnetic field is slowly varying in time and space, the magnetic moment,

$$\mu = \frac{E_\perp}{B} = \frac{m v_\perp^2}{2B}$$

is constant. In the absence of collisions, the constancy of the magnetic moment makes it possible to obtain a relationship between the time rate of change of the perpendicular component of the energy, and the time rate of change of magnetic field. Thus. we have

$$\frac{d\mu}{dt} = o = \frac{1}{B}\frac{dE_\perp}{dt} - \frac{E_\perp}{B^2}\frac{dB}{dt}, \tag{2}$$

from which we obtain

$$\frac{dE_\perp}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} \tag{3}$$

The total energy E of the ions is given by

$$E = E_{11} + E_\perp , \tag{4}$$

where E_{11} is the ion energy along the magnetic field lines, and $E_\perp$ is the ion energy perpendicular to the magnetic field lines, with two degrees of freedom. If no collisions occur, the perpendicular component of the ion energy, $E_\perp$, oscillates with the frequency ω, and no net heating occurs. If collisions do occur, however, some of the energy in the perpendicular component is transferred to the parallel component E_{11}. In kinetic equilibrium, the parallel component of the energy will be equal to one half the perpendicular component, as a result of equipartition. When the perpendicular component is driven by magnetic pumping, a periodic departure from equipartition occurs, and energy can be transferred between the parallel and perpendicular components. This may be expressed mathematically by adding a collisional term to Equation (3),

$$\frac{dE_\perp}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} - v_c\left(\frac{E_\perp}{2} - E_{11}\right), \tag{5}$$

and

$$\frac{dE_{11}}{dt} = v_c\left(\frac{E_\perp}{2} - E_{11}\right), \tag{6}$$

where v_c is the collision frequency. Now summing Equations (5) and (6) and using Equation (4) one obtains:

$$\frac{dE}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} \tag{7}$$

Thus, the rate of change of the total ion energy is proportional to the magnetic moment, and the time rate of change of the magnetic field. The net energy transfer can be obtained by taking the second derivative of Equation (7) and then using Equations (5) and (6) to eliminate the first derivative of the parallel and perpendicular components of the energy. Further, using Equation (7) itself to eliminate the perpendicular component of energy, we obtain:

$$\frac{d^2E}{dt^2} - \left[-\frac{3}{2}v_c + \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right]\frac{dE}{dt} \tag{8}$$

$$-\frac{v_c}{B}\frac{dB}{dt}E = 0.$$

Now if the sinusoidally varying magnetic field given by Equation (1) is assumed, Equation (8) becomes:

$$\frac{d^2E}{dt^2} - \left[-\frac{3}{2}v_c + \frac{\omega\cos\omega t}{\sin\omega t}\right]\frac{dE}{dt} \tag{9}$$

$$-\frac{\delta v_c\,\omega\sin\omega t}{1+\delta\cos\omega t}E = 0.$$

This is a differential equation for the change i. energy due to collisional magnetic pumping. It is a differential equation with periodic coefficients. It can be solved by using Floquet theory along with a perturbation treatment. Since $\delta << 1$ the term $(1 + \delta\cos\omega t)^{-1}$ can be expanded in a Taylor series

$$(1+\delta\cos\omega t)^{-1} \approx 1 - \delta\cos\omega t + \ldots\ldots \tag{10}$$

Substituting (10) into (9), we obtain

$$\frac{d^2E}{dt^2} - \left[-\frac{3}{2}v_c + \frac{\omega\cos\omega t}{\sin\omega t}\right]\frac{dE}{dt} \tag{11}$$

$$+\ \delta v_c\,\omega\sin\omega t(1 - \delta\cos\omega t)E = 0$$

From Floquet theory, the solution to Equation (11) takes the following form.

$$E = a_1 e^{\lambda_1 t} p_1(t) + a_2 e^{\lambda_2 t} p_2(t) \tag{12}$$

$p_1(t)$ and $p_2(t)$ are periodic functions with a period $2\pi/\omega$. Using a perturbation treatment, λ_1 and λ_2 are found to be:

$$\lambda_1 = -\frac{3}{2}v_c + \delta\ell_1 + \delta^2\ell_2 + \ldots\ldots \tag{13}$$

$$\lambda_2 = \delta\ell_1 + \delta^2\ell_2 + \ldots\ldots \tag{14}$$

The solution associated with λ_1 is damped in time and dosen't contribute to the heating mechanism, and

therefore it will be dropped. The solution associated with λ_2 will represent heating, so from now on we will assume a solution $E = e^{\lambda 2t} p_2(t)$. To find the rate of change of energy we solve for $p_2(t)$ and put the secular terms equal to zero. To do so, let's use a perturbation treatment. We take

$$p_2(t) = p_{20}(t) + \delta p_{21}(t) + \delta^2 p_{22}(t) + \ldots, \tag{15}$$

where p_{20} is the background value, and we set it equal to 1 for normalization purposes. Now let's solve the differential equation (11) for the first power of the parameter δ. We get

$$\frac{d^2P_{21}}{dt^2} + \left[\frac{3v_c}{2} - \text{ctn}\,\omega t\right]\frac{dP_{21}}{dt} = \tag{16}$$

$$-\frac{3}{2}\ell_1 v_c + \ell_1 \omega\,\text{ctn}\,\omega t - v_c\,\omega \sin \omega t .$$

The homogeneous solution of Equation (16) is:

$$P_{21}(t) = C_1 e^{-\frac{3v_c}{2}t}\left\{a \cos \omega t + b \sin \omega t\right\} + C_2, \tag{17}$$

where

$$a = \frac{-\omega}{\omega^2 + \frac{9}{4}v_c^2}, \tag{18}$$

and

$$a = \frac{-\frac{3}{2}v_c}{\omega^2 + \frac{9}{4}v_c^2}. \tag{19}$$

The particular solution of Equation (16) is

$$p_{21}(t) = -\ell_1 t + v_c\, a \sin \omega t \tag{20}$$

$$- v_c\, b \cos \omega t + \ell_1\, a\, \text{ctn}\,\omega t$$

$$+\left(\frac{-\ell_1}{\sin \omega t} - \frac{2}{3}\omega\right)\left(a \cos \omega t + b \sin \omega t\right).$$

Now setting the secular term to zero provides us with the result

$$\ell_1 = o. \tag{21}$$

From the previous result we know that the rate of change is proportional to a higher power of δ. So we solve the differential equation for the second power of δ. We get the following differential equation,

$$\frac{d^2P_{22}}{dt^2} + \left(\frac{3}{2}v_c - \omega\,\text{ctn}\,\omega t\right)\frac{dP_{22}}{dt} = -\frac{3}{2}\ell_2 v_c \tag{22}$$

$$+ \ell_2\,\omega\,\text{ctn}\,\omega t + v_c\,\omega \sin \omega t \cos \omega t$$

$$- v_c\,\omega \sin \omega t\, P_{21}(t)$$

As in the previous case the interesting part of the solution is the particular solution, and the important part of the particular solution is the part containing the secular term. The latter is found to be:

$$\left(\frac{3}{2}\ell_2 v_c b + a\,\ell_2\,\omega - \frac{1}{6}v_c\,\omega\, a\right)t \tag{23}$$

Setting this term to zero we get

$$\ell_2 = \frac{v_c\,\omega^2}{6(\omega^2 + \frac{9}{4}v_c^2)} \tag{24}$$

The growing part of the solution to Equation (11) can thus be written:

$$E = \ell^{\lambda_2 t} p_2(t) \tag{25}$$

$$= e^{\delta^2 \ell_2 t + \ldots}(E_o + \delta p_{21} + \delta^2 p_{22} + \ldots).$$

The term

$$e^{\lambda_2 t} = e^{\delta^2 \ell_2 t + \ldots}$$

can be expanded to

$$e^{\lambda_2 t} = 1 + \delta^2 \ell_2 \ell + \ldots \tag{26}$$

Inserting Equation (26) into Equation (25) an increase of energy in a time $2\pi/\omega$ is found to be.

$$\Delta E = \delta^2 \ell_2 \frac{2\pi}{\omega} E_o \tag{27}$$

Now inserting Equation (24) into Equation (27) we get:

$$\Delta E = \delta^2 E_o \frac{\pi}{3}\frac{v_c\,\omega}{\frac{9}{4}v_c^2 + \omega^2} \tag{28}$$

Equation (28) can also be written as:

$$\frac{dE}{dt} = \frac{\delta^2}{6}\frac{v_c\,\omega^2}{\frac{9}{4}v_c^2 + \omega^2}E. \tag{29}$$

This result agrees well with the one found by Burger et al[5]. We define the heating time as:

$$\tau_H \quad \frac{6\left(\frac{9}{4}v_c^2+\omega^2\right)}{\delta^2\omega^2 v_c}, \tag{30}$$

so

$$\frac{dE}{dt}=\frac{E}{\tau_H}. \tag{31}$$

The heating rate coefficient is defined as

$$a=\frac{1}{\tau_H}. \tag{32}$$

Two limiting cases exist, the highly collisional case and the relatively collisionless case. When the plasma is highly collisional we have $v_c >> \omega$, and Equation (29) can be approximated by

$$\frac{dE}{dt} \approx \frac{2}{27}\frac{\delta^2\omega^2}{v_c}E. \tag{33}$$

The maximum value that the heating rate coefficient can take with respect to v_c is calculated from the following equation:

$$\frac{da}{dv_c}=0, \tag{34}$$

and

$$a_{max}=\frac{\delta^2 v_c}{12}. \tag{35}$$

The frequency at which a_{max} occurs is

$$\omega=\frac{3}{2}v_c. \tag{36}$$

If we operate at a_{max}, the inequalities we must satisfy are

$$\omega=\frac{3}{2}v_c << \omega_{ci}, \tag{37}$$

and

$$\tau_H=\frac{12}{\delta^2 v_c} < \frac{L}{V_i}=\tau_{tr}. \tag{38}$$

The second case is when the plasma is relatively collisionless. In this case we have $\omega >> v_c$, and Equation (29) can be approximated by

$$\frac{dE}{dt}=\frac{\delta^2 v_c}{6}E. \tag{39}$$

To get a feeling on how different are the rates of energy increase in the above two cases, let's consider a fusion plasma operating at the following parameters: T_i = 1 keV; A = 2; n = $10^{19}/m^3$; L = 0.5 m; B = 2.0 T. The collision frequency in this case is $v_c \approx$ 313 Hz leading to a heating rate coefficient

$$a=\frac{\delta^2 v_c}{6}=52\,\delta^2/\mathrm{sec}. \tag{40}$$

Now if anomalous conductivity is present in the plasma, the collision frequency can be in the order of 5 MHz, leading to a maximum heating rate coefficient of

$$a_{max}=\frac{\delta^2 v_c}{12}=4.2\,10^5\,\delta^2/\mathrm{sec},$$

so it can be seen that if anomalous collisions frequencies occur in the right range, an improvement of ~ 10^4 heating effectiveness can be made.

APPROXIMATE SOLUTION TO THE SAWTOOTH PERTURBATION

Let's now consider the following magnetic perturbation,

$$B=B_0\left(1+\delta\frac{t}{t_1}\right)\text{from } t=0 \text{ to } t=t_1,$$

$$B=B_0\left(1+\delta\left(-\frac{t}{t_L}+\frac{t_2}{t_L}\right)\right)\text{from } t=t_1 \text{ to } t=t_2$$

$$\text{with } t_L=t_2-t_1.$$

The wave-form is periodic with a period T = t_2. To satisfy the condition of adiabaticity, we have the following

$$t_{ci} << t_{coll} \approx t_2 \le t_{tr}.$$

The differential equation for the change in energy due to collisional magnetic pumping assumes the following form when $t \le t_1$,

$$\frac{d^2E}{dt^2}+\frac{3}{2}v_c\frac{dE}{dt}-v_c\frac{\delta/t_1}{1+\delta t/t_1}E=0 \tag{41}$$

For $\delta t/t_1 << 1$ the above equation becomes

$$\frac{d^2E}{dt^2}+\frac{3}{2}v_c\frac{dE}{dt}-v_c\frac{\delta}{t_1}E=0. \tag{42}$$

The solution of Equation (42) is

$$E=C_1e^{r_1t}+C_2e^{r_2t},$$

with

$$r_1 = \frac{3}{4} v_c \left(-1 + \left(1 + 16/9 \frac{\delta}{v_c t_1}\right)^{\frac{1}{2}}\right),$$

$$r_2 = \frac{3}{4} v_c \left(-1 - \left(1 + 16/9 \frac{\delta}{v_c t_1}\right)^{\frac{1}{2}}\right).$$

Let's assume that $\delta / v_c t_1 \; 16/9 << 1$ so that

$$\left(1 + \frac{16}{9} \frac{\delta}{v_c t_1}\right)^{\frac{1}{2}} \approx 1 + \frac{8}{9} \frac{\delta}{v_c t_1} + \ldots .$$

r_1 and r_2 are then equal to

$$r_1 = \frac{2}{3} \frac{\delta}{t_1} ,$$

$$r_2 = -\frac{3}{4} v_c \left(2 + \frac{8}{9} \frac{\delta}{v_c t_1}\right),$$

with the boundary conditions

$$E(o) = E_o$$

$$\left.\frac{dE}{dt}\right|_{t=o} = \frac{\delta}{t_1} \frac{2}{3} E_o . \tag{43}$$

The solution of the differential equation is

$$E = E_o e^{2/3 \delta \frac{t}{t_1}} . \tag{44}$$

At $t = t_1$ $E = E_0 e^{2/3 \delta} \sim E_0 (1 + 2/3 \delta)$. The heating rate during the ramping up part of the cycle is then:

$$\frac{dE}{dt} = \frac{2 \delta E_o}{3 t_1} . \tag{45}$$

For the ramping-down part of the cycle, the differential equation for the first power of δ is

$$\frac{d^2E}{dt^2} + \frac{3}{2} v_c \frac{dE}{dt} \quad \frac{v_c}{t_L} E = o . \tag{46}$$

The boundary conditions are

$$E(t_1) = E_o (1 + \frac{2}{3} \delta) , \tag{47}$$

$$\left.\frac{dE}{dt}\right|_{t=t_1} = \frac{E_\perp}{B} \left.\frac{dB}{dt}\right|_{t=t_1} \approx \frac{2}{3} E(t_1) \left(-\frac{\delta}{t_L}\right).$$

The second boundary condition assumes that enough collisions occur leading to equipartition. The solution to Equation (46) is:

$$E(t) = C_1 e^{-\frac{2}{3}\frac{\delta}{t_L}} + C_2 e^{-\frac{3}{2} v_c t} e^{\frac{2}{3}\frac{\delta}{t_L} t} . \tag{48}$$

As is seen from the form of E(t), it is damped in time and the contribution to heating is small. The heating rate is basically equal to

$$\frac{dE}{dt} \sim \frac{2 \delta E_o}{3 t_1} .$$

Note that $1/t_1$ is approximately the pumping frequency so

$$\frac{dE}{dt} \sim K \delta \omega E_o , \tag{49}$$

K is a constant.

The above treatment shows that a heating rate proportional to the first power of δ is possible to achieve. A more in depth approach will be given in later work, where a condition to get first order heating is found.

CONCLUSION

Collisional magnetic pumping can be a very effective way to heat plasmas. For plasma with a high level of turbulence like the one studied in the UTK Plasma Laboratory, the collision frequency can be several MHz, leading to an enhanced heating rate due to collisional magnetic pumping. The classical heating rate that has been derived for a sinusoidal magnetic perturbation is proportional to the square of the modulation of the field δ. We have shown that with another form of perturbation a heating rate proportional to the first power of δ can be achieved. Since δ is a small number, the first order heating rate can be several hundred times larger than the classical one.

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An MHD Model for the Earth's Magnetic Field with Spatially Dependent Electrical Conductivity

I. Alexeff
J. R. Roth

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An MHD Model for the Earth's Magnetic Field with Spatially Dependent Electrical Conductivity

IGOR ALEXEFF, FELLOW, IEEE, AND J. REECE ROTH, FELLOW, IEEE

***Abstract*—A simple model demonstrates that symmetrical fluid flow in the earth's core can maintain a steady-state magnetic field if the electrical conductivity is allowed to vary as a function of radius (temperature).**

THIS paper was inspired by an invited talk on geomagnetic fields by Dr. Radler of the German Democratic Republic at the Autumn Plasma School in the Georgian Soviet Socialist Republic in 1984. He very clearly pointed out the complexities of present MHD models [1], and we came to suspect that some simplifying assumption was missing. Conventional dc generators contain an item missing in these MHD models—a set of brushes. A similar mechanism—a change of electrical conductivity as a function of position during the cyclical flow pattern—is not present in these models.

An example of such a flow pattern is given in Fig. 1. Fluid descending at the equator of a planet's flow pattern carries magnetic field lines toward the core, opposing the outward diffusion of the field lines due to finite conductivity. In the core, the fluid flow is along the field lines to the magnetic axis, so no MHD effect is invoked. However (the new point), the flow from the magnetic axis back to the magnetic equator occurs near the surface. This flow takes place at a lower temperature and consequently at a lower conductivity than that of the descending fluid. Thus any tendency of the flow near the surface to carry field lines of the opposite polarity back into the descending fluid is greatly reduced.

To a first approximation, the fluid flow in the geomagnetic equator appears as a continually in-flowing disc, with a source at the outer edge, and a sink at the center as shown in Fig. 2. A one-dimensional slab model can be used as a first approximation to the equatorial disc, shown in Fig. 3. Here the slab is infinite in the x direction. The fluid appears at a finite radius y_0 (the equatorial radius), and disappears at $y = 0$ (the magnetic axis). The magnetic field points in the z direction. Of course, the fluid cannot physically appear and disappear, since $\nabla \cdot v = 0$, but a conducting fluid can electrically appear and disappear as the conductivity is turned on and off, analogous to the action of a commutator. Note that the conductivity does not need to go to zero. The differential conductivity is what really matters. A model of this process can be made

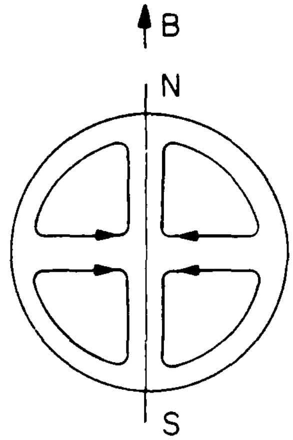

Fig. 1. Flow pattern in earth's core.

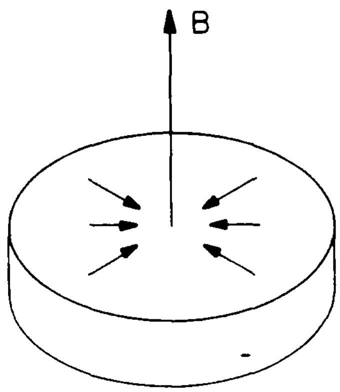

Fig. 2. Simplified flow pattern.

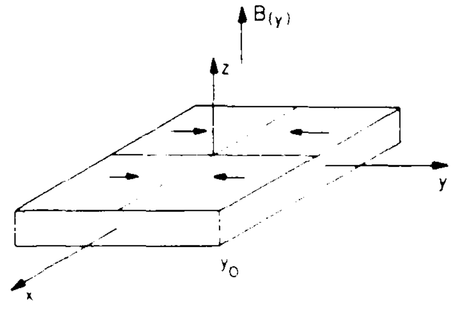

Fig. 3. Slab model.

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The authors are with the Department of Electrical Engineering, College of Engineering, University of Tennessee, Knoxville, TN 37996-2100.

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by using flowing mercury. The conductivity disappears when the fluid flows into parallel insulated channels. If the fluid conductivity were to decrease with increasing temperature, the same model would hold, but the flow pattern would be reversed. The critical point is that the fluid have a change in conductivity at a fixed point in space.

Mathematically, we proceed from the MHD equations:

$$\nabla \times \vec{B} = \mu_0 \vec{j}$$

$$\vec{j} = \sigma(\vec{E} + \vec{v} \times \vec{B})$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times (\nabla \times \vec{B}) = \nabla(\nabla \cdot \vec{B}) - \nabla^2 \vec{B} = \mu_0 \nabla \times \vec{j}$$

$$= \mu_0\sigma(\nabla \times \vec{E} + \nabla \times (\vec{v} \times \vec{B}))$$

$$= \mu_0\sigma\left(-\frac{\partial \vec{B}}{\partial t} + \nabla \times (\vec{v} \times \vec{B})\right).$$

As $\nabla \cdot \vec{B} = 0$, our final result is

$$\nabla^2 \vec{B} = \mu_0\sigma\left(\frac{\partial \vec{B}}{\partial t} - \nabla \times (\vec{v} \times \vec{B})\right).$$

Expanding the third term, we find

$$\frac{1}{\mu_0\sigma} \nabla^2 \vec{B} = \frac{\partial \vec{B}}{\partial t} - (\vec{v}(\nabla \cdot \vec{B})$$

$$- \vec{B}(\nabla \cdot \vec{v}) + (\vec{B} \cdot \nabla)\vec{v} - (\vec{v} \cdot \nabla)\vec{B}).$$

In a system with no flow and finite size, we find that $\nabla^2 \vec{B}$ must be negative. Therefore $\partial \vec{B}/\partial t$ is negative, and the magnetic field decays. However, we shall now demonstrate that the $\vec{B}(\nabla \cdot \vec{v})$ term balances this loss process.

Let us examine the other terms. Obviously, the term $\vec{v}(\nabla \cdot \vec{B}) = 0$. Two other terms are obtained by the details of our model. We assume that

$$\vec{B} = \vec{k} B(y)$$

$$\vec{v} = -\vec{j}\, v_0 \operatorname{sgn} y \quad \text{for} \quad |y| < y_0$$

$$= 0 \quad \text{for} \quad |y| > y_0.$$

We obtain

$$\frac{1}{\mu_0\sigma} \nabla^2 \vec{B}_z = \frac{\partial \vec{B}_z}{\partial t} + \vec{B}_z\left(\frac{\partial}{\partial y} \vec{v}\right) - B_z \frac{\partial}{\partial z} \vec{v} + v_0 \frac{\partial B_z}{\partial y}.$$

The term $-v_0(\partial B_z/\partial y)$ is due to flux being carried along

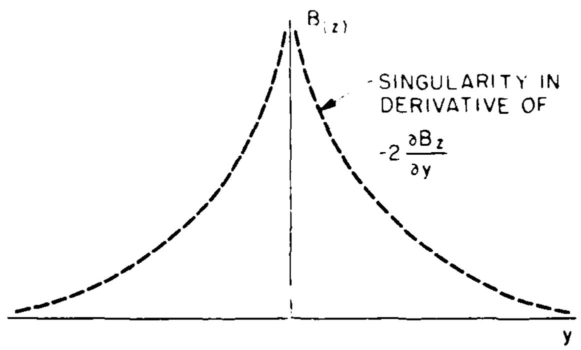

Fig. 4. Plot of magnetic field as a function of radius.

by a conducting fluid, as found by Alfvén. We obtain

$$\frac{1}{\mu_0\sigma}\frac{\partial^2 B_z}{\partial y^2} = \frac{\partial B_z}{\partial t} + B_z(-v_0(2\delta(y))) - v_0 \operatorname{sgn}(y) \frac{\partial B_z}{\partial y}$$

$$\frac{1}{\mu_0\sigma}\frac{\partial^2 B_z}{\partial y^2} + 2v_0 B_z \delta(y)$$

$$+ v_0 \frac{\partial B_z}{\partial y} \operatorname{sgn}(y) = \frac{\partial B_z}{\partial t}.$$

Assume $\partial B_z/\partial t = 0$:

$$\frac{1}{\mu_0\sigma}\frac{\partial^2 B_z}{\partial y^2} + 2v_0 B_z \delta(y) + v_0 \frac{\partial B_z}{\partial y} \operatorname{sgn}(y) = 0.$$

Assume symmetry about $y = 0$:

$$\frac{1}{\mu_0\sigma}\frac{\partial^2 B_z}{\partial y^2} + v_0 B_z \delta(y) + v_0 \frac{\partial B_z}{\partial y} = 0, \qquad 0 \leq y \leq y_0.$$

Except for the end points, the differential equation is easy to solve. Let $B(z) = B_0 e^{\gamma y}$. We obtain

$$\frac{1}{\mu_0\sigma}\gamma^2 + v_0\gamma = 0.$$

The values for γ are

$$\gamma = 0$$

$$\gamma = -v_0\mu_0\sigma.$$

Thus there are two independent solutions:

$$B(z) = B_0 e^{-v_0\mu_0\sigma y} + B_1.$$

The term B_0 shows the magnetic flux compressed along the axis due to the in-flowing conducting fluid, while the term B_1 can be used to fix the boundary condition.

The effect of the $\delta(y)$ function at the origin is easily seen. If we match the flows from $+y$ and $-y$, there is a singularity in the derivative at the origin, as shown in Fig. 4. The $\delta(y)$ function absorbs this singularity, by causing a rapid change in the second derivative at the origin. If we integrate the equation across the singularity, we obtain

$$\frac{\partial B_z}{\partial y_2} - \frac{\partial B_z}{\partial y_1} = -2B_z v_0\mu_0\sigma.$$

Actually, what is occurring is that the inward convected flux from one side impinges on the incoming flux from the other side. In actual practice, there is a neutral-flow region between the two incoming streams where the flux accumulates.

As was quite properly pointed out by a reviewer, the case in which $(1/\mu_0\sigma)\gamma^2 + v_0\gamma = 0$ is a singular point. In general, this quantity initially is either greater than or less than zero. We can discuss this more general solution by assuming that $B(z) = B_0 e^{\gamma y + \alpha t}$. In this case, our eigenvalue equation becomes $(1/\mu_0\sigma)\gamma^2 + v_0\gamma = +\alpha$. If v_0 is sufficiently small, then α is negative, and the solution decays away in time. On the other hand, if v_0 is sufficiently large, then α is positive, and the solution grows. Exponential growth will be limited by a nonlinear term in the differential equation. Specifically, when the gradient of the magnetic pressure $B^2/2\mu_0$ approaches the gradient of the thermal pressure that drives the velocity of the magma v_0, then this velocity will decrease, and the magnetic field growth will saturate. In this case, the problem has become a more complex nonlinear one. However, we can state that the equation $(1/\mu_0\sigma)\gamma^2\ v_{0\gamma} = 0$ forms the boundary between decaying solutions and growing solutions that lead to stable but nonlinear states.

If v_0 is assumed to be the flow value *resulting* from the balance of magnetic and thermal pressure, then our original equation is correct. This is what we had initially assumed but neglected to state.

Let us now estimate the value of the quantity for the e-folding distance of the current layer $1/v_0\sigma\mu_0$ in the interior of the earth. The value for μ_0 in the hot magma is obviously 1.26×10^{-6} H/m. The conductivity σ is estimated to be 3×10^5 mho/m [2]. The velocity in the core is estimated to be 4×10^{-4} m/s [3]. This velocity corresponds to our one good probe of core motion—the observed westward drift of the magnetic poles—and not the much slower velocity of the crustal plates (cm per year). Thus $y = (4 \times 10^{-4} \times 3 \times 10^5 \times 1.26 \times 10^{-6})^{-1} =$ 6613 m, or 6 km, or about 10^{-3} of the earth's radius (6366 km). Thus these quantities suggest a highly compressed magnetic field near the earth's core!

Conclusions

We have derived a quite simple model for a steady-state magnetic field for the earth and for other astronomical objects as well. We have not treated the problems of the origin of the field or of its reversals over geologic time. In addition to the dynamo theories of others, let us propose the concept of flux trapping. If the earth were to pass through a weak magnetic field in space, the fluid becoming conducting at the surface would trap this flux and concentrate it in the core. This would provide the planet with an original field. We also note that the present internal field shows up as a reversed surface field. This also could be trapped and convected inward, providing periodic field reversals.

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Steady-State Orbitron Emissions

M. Rader
F. Dyer
I. Alexeff

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Steady-State Orbitron Emissions

MARK RADER, STUDENT MEMBER, IEEE, FRED DYER, MEMBER, IEEE, AND IGOR ALEXEFF, FELLOW, IEEE

***Abstract*—The Orbitron maser has been operated at a pressure of 2 × 10^{-6} in the steady state. Electrons are supplied to the device by an oxide-coated tungsten cathode placed inside the cylindrical cavity. The plasma-free emission corresponded to harmonically related steady-state narrow lines. The fundamental (lowest frequency) line corresponds to a resonance in the cavity system, which could be observed with a grid-dip meter.**

I. Introduction

On September 3, 1985, the first steady-state high-vacuum Orbitron maser [1] emissions were observed. These emissions were from a device in a high vacuum of 5 × 10^{-6} torr produced by an oil diffusion pump trapped by a liquid-nitrogen-cooled baffle. The electron feed for this device was provided by an axial hot cathode in a cylindrical cavity. To demonstrate that no plasma was present to produce plasma oscillations, as claimed by others [2], [3], we monitored the presence of plasma in the cavity of this tube and many of the subsequent devices with a Langmuir probe. This device has since undergone many design revisions as the design theory has been better understood. These changes include multiple anode wires, changing the electron feed system, and the suppression of low-frequency resonances by excluding large orbit electrons from the device. This paper will describe these experiments and others using a gas-filled pulsed Orbitron.

II. Theory

The Orbitron operates by means of a very simple physical mechanism. Electrons are injected into a coaxial system in which there is a potential well present. These electrons, because of their angular momentum, orbit the central wire, and generate radiation as they lose energy and fall closer to the wire. The physical mechanism by which the Orbitron generates radiation is known as a negative mass instability. This is the same mechanism by which gyrotrons [4] operate, but important differences lie in the types of electron confinement used in this device and in the electron kinetic energies involved. In order to explain these differences and how this device works, one must look at the basic Orbitron configuration as illustrated in Fig. 1(a). The internal structure of the Orbitron is characterized by a wire radius r_0, a wall radius r_1, and a dif-

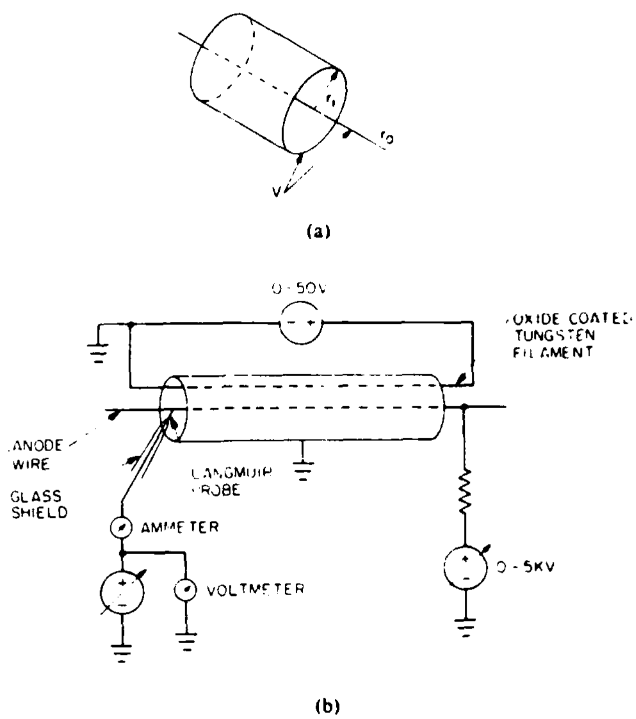

Fig. 1. (a) Basic Orbitron diagram. (b) Orbitron schematic.

ference in potential V between the inner conductor (V_{wire}) and the outer cavity (V_{wall}). The difference in potentials is such that $V_{wire} > V_{wall}$. Electrons injected into this system are electrostatically confined in a potential well and orbit the central wire in a natural population inversion. This population inversion is caused by the loss of electrons from the system through impact on the wire. This system is also naturally negative mass unstable and so can use electrons with a low kinetic energy [1]. This is in contrast to the relativistic energies required by gyrotrons to achieve a negative mass instability. The gyrotron also requires an electron dumping mechanism needed to achieve a population inversion while the Orbitron has this as a natural result of its confinement system. The term negative mass comes from the fact that, in this system, as the electrons lose energy they fall in orbital radius and gain orbital angular velocity [4].

The Orbitron also has an advantage in frequency range over the gyrotron. For circular electron orbits, the highest angular frequency (w)[1] an Orbitron will produce is given by

$$w = 1/r_0 \times \left(eV(m \times \ln(r_1/r_0))^{-1}\right)^{1/2}.$$

This only differs from highly elliptical orbits by a factor

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The authors are with the Electrical Engineering Department, University of Tennessee, Knoxville, TN 37996-2100.

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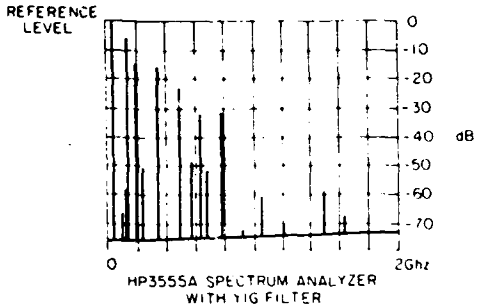

Fig. 2. First Orbitron spectra.

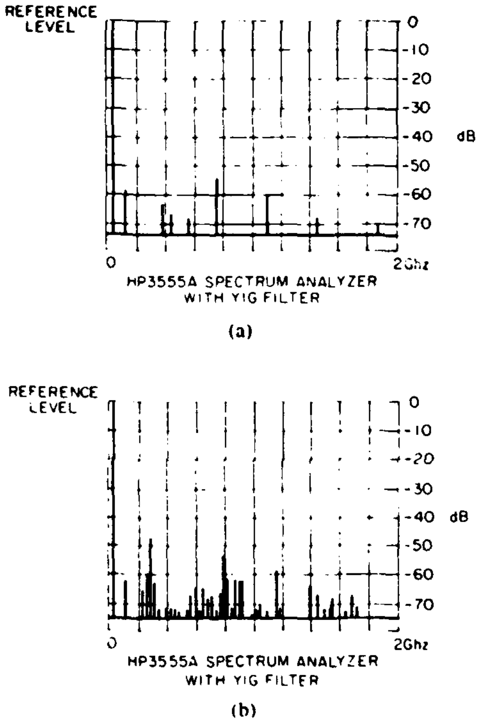

Fig. 3. (a) One-wire comparison. (b) Two-wire comparison.

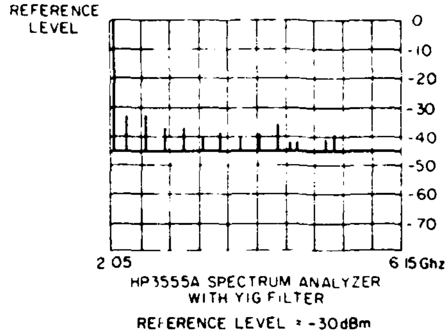

Fig. 4. Four-wire spectra.

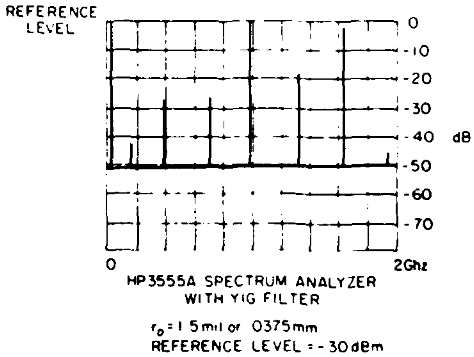

Fig. 5. Seven-wire spectra.

of $(\pi/2)^{1/2}$. So the frequency is only limited by the highest voltage available and the size of the center wire [5]. In a gyrotron the frequency is limited by the magnitude of the magnetic field that can be produced. The highest possible angular frequency of a gyrotron is eB/m_e. A pulsed magnetic field of approximately 24 T is the strongest magnetic field that has been obtained in this type of device. This corresponds to a wavelength of about $\frac{1}{3}$ mm[6].

III. Steady-State Emissions

On September 3, 1985, the first high-vacuum orbitron emissions were observed. These emissions have led to a series of proof of principle experiments. There have been three distinct groups of these experiments, and these are what will be explored.

In the first group of experiments, open cavities between 5 and 10 cm in length were used with a diameter of between 1 and 2 cm. These cavities generated a series of harmonics for which the fundamental was determined by an external cavity cable resonance. Fig. 2 shows the first of these experiments. It was operated at a pressure of 5×10^{-6} torr at a wire potential of 500 V and a current in the center wire of 40 mA. The radius of the center wire was 3 mils or 0.075 mm.

This cavity and subsequent cavities of this group of experiments were monitored for the presence of plasma with a Langmuir probe. There were no indications of a plasma except for a few microamperes of electron current, which originated from the hot filament. The next step was to increase the number of anode wires from one to two. This was done in the belief that this would increase the power output and the frequency range.

Fig. 3 is a comparison between one and two center wires. The pressure was at 5×10^{-6} torr and the voltage in the top spectral picture was 1.2 kV, while at the bottom it was 800 V. Both had a current of about 34 mA on the center wire. Some nonharmonic frequencies can be seen in the two-wire spectral picture. These go away as the current or the voltage is increased and what appears to be phase locking occurs between the wires.

The number of center wires was increased to four and the power and the apparent phase locking increased significantly, but more importantly, the frequency of emission went up sharply. Fig. 4 is an example of this. The input operating voltage to this device was 500 V, and the current through the center wire radius was 3 mils or 0.075 mm. Under these operating conditions the highest circular

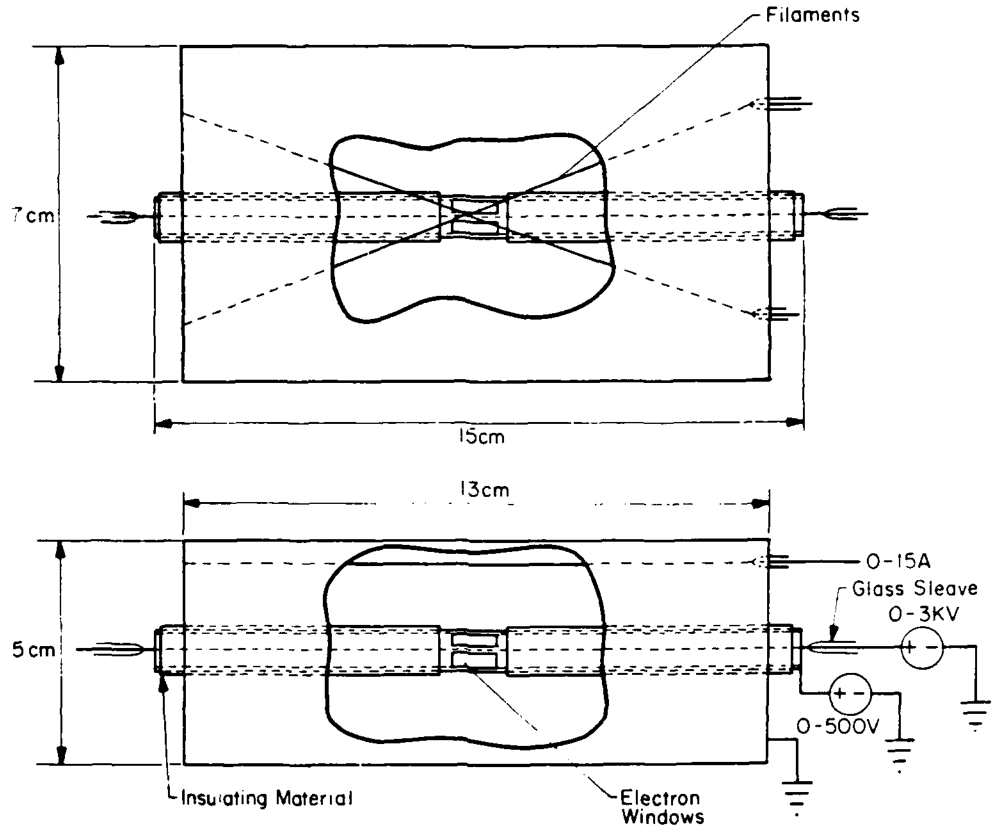

Fig. 6. Double cavity schematic.

frequency is 8.3 GHz, and so this is within a factor of 1.5 of what is shown below.

In the next experiments, the number of center wires was increased to seven. It significantly increased the output amplitude, as seen in Fig. 5, with less current required for what appears to be phase locking. In Fig. 5 the center wire voltage was 500 V at 20 mA. The pressure was 2 $\times$ 10^{-6} torr.

In the second group of experiments an attempt was made to control the fundamental frequency by changing the cavity structure. In order to do this, it was necessary to reduce the cavity radius so that large low-frequency orbits would not fit inside the cavity at low to moderate voltages. This was accomplished by constructing the double cavity system shown in Fig. 6.

This device met with limited success. While it was possible to control the fundamental frequency with a cavity mode, as demonstrated in Fig. 7, it required an accelerating voltage on the secondary cavity and had very small wire currents.

In the third group of experiments, the configuration was changed back to the original design with a cavity length of 15 cm, but the reduced cavity radius was kept. This worked extremely well. The frequencies observed corresponded to the fundamental TEM modes of the cavity. This was observed on two receivers, as demonstrated in Figs. 8 and 9. The power output from this device was greater than previously observed and in some cases was

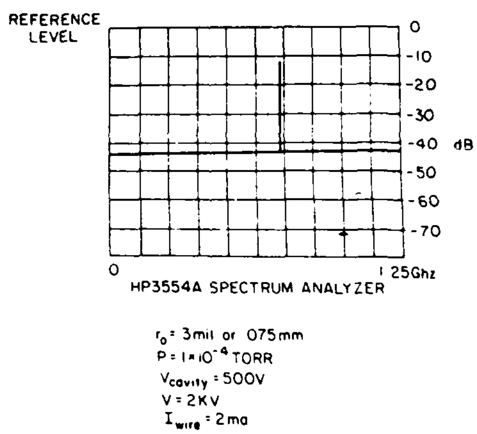

Fig. 7. Double cavity spectra.

seen to be -10 dBm at one frequency, as seen in Fig. 9, with a correction for horn and cable losses included. This is the power observed impinging on the receiving horn, and not that radiated over all space. Assuming that the power is radiated uniformly over free space and knowing the horn area (0.391 m^2), the radius from which the data were taken (0.15 m), and the power used by the device (4.2 W), it is possible to estimate the efficiency of the device which is about 0.01 percent, but this is only the efficiency at one frequency. To get the overall efficiency one must take into account the power radiated at other frequencies.

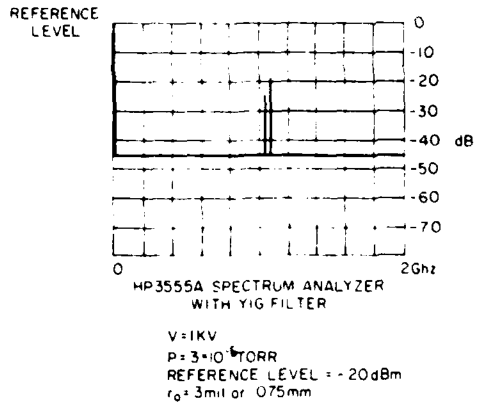

Fig. 8. Hewlett-Packard spectra.

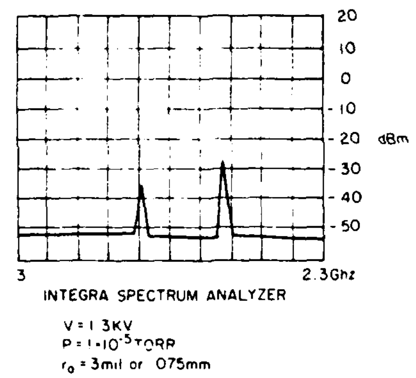

Fig. 9. Integra spectra.

In these devices, it has been found that a difference in potential of only 40 V is required for noticeable emission to occur with a starting current of about 8 mA, but this starting current was reduced to the order of 0.5 mA or less as the voltage was raised to 300 V or higher. This start current appears to be highly dependent upon the Q of the resonant system [5]. To eliminate the possibility of signal imaging and spurious responses in our spectral analysis, a YIG-tuned filter or other filter designed to eliminate aliasing was attached to the spectrum analyzers when necessary.

IV. Pulsed Emissions

The pulsed Orbitron appears to work by the same mechanism as the steady-state Orbitron except that electrons are supplied by a cold cathode discharge which ionizes any gas in the tube. Ions are collected by the cathode wall and electrons from the gas are trapped in orbit around the positive central wire and cause the Orbitron effect. The gas pressure in these tubes ranges from 50 to 0.1 mtorr, depending on the tube.

While the operating mechanism of the steady-state version of this tube appears to be well understood, there are still some questions about the operating mechanism of the pulsed device [2], [3]. To dispel these doubts, there has been a series of experimental attempts to ensure that the operating mechanism is properly understood.

The experimental work included probing the working tube with a microwave signal to determine the plasma cutoff frequency. This was found to be as low as one quarter of the emitted frequency. This suggests that plasma oscillations are not the fundamental emission process. Also tried was lining $\frac{9}{10}$ of the cathode tube with a high-voltage insulating material, as shown schematically in Fig. 10, to eliminate two-beam plasma interactions which were suggested as the fundamental emission mechanism [2], [3]. In this experiment, it was found that with all other conditions the same, there is little to no change in the emission characteristics.

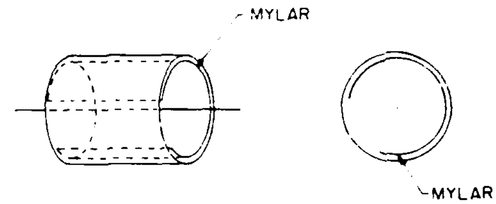

Fig. 10. Insulated cavity.

In this pulsed gas-filled tube, a much higher voltage can be used, as well as a thinner wire. In this mode of operation, detection of submillimeter wavelengths is routine, and we have obtained radiation at 1 THz (0.3 mm). The peak microwave power output is about 1.5 W at 1 THz and about 50 W at frequencies around 100 GHz. Efficiencies range from 1 percent at 3.5 GHz to 0.001 percent at 1 THz [7]. While the power may seem low, it must be remembered that many of these frequencies are emitted simultaneously from one tube with the same power levels.

V. Conclusion

It has been demonstrated that the steady-state Orbitron is an operational device, and that it appears to operate in the way our assumptions predict. There is evidence that the pulsed Orbitron also works according to the same theory. Both the pulsed and steady-state Orbitrons offer an alternative to the main-line concepts now in use for high-frequency microwave production. In these experiments, many of the concepts of the steady-state Orbitron have been introduced and shown to hold true. While the steady-state frequency limit demonstrated is not yet that of the pulsed Orbitron, it is believed that this can be improved to higher frequency ranges.

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Selection of books for review is based on the editor's opinions regarding possible reader interest and on the availability of the book to the editor. Occasional selections may include books on topics somewhat peripheral to the subject matter ordinarily considered acceptable.

Introduction to Fusion Energy

Author	J. Reece Roth
Publisher	Ibis Inc., Charlottesville, Virginia (1986)
Pages	650 + xii
Price	$35.00
Reviewer	Chan K. Choi

This book is an introductory level textbook on fusion for college juniors and seniors with emphasis on magnetically confined plasmas. This is a welcome addition to existing fusion textbooks at this level. It covers quite effectively not only the basic physical processes on fusion-related plasmas and the major fusion reactor concepts, but also describes quite well the alternate confinement approaches including many useful applications.

The first four chapters introduce the basic plasma physics, including single-particle confinement, plasma transport, equilibrium, and instability. Plasma heating and refueling, fusion reactions, and the plasma particle and energy balance are treated in Chaps. 5, 6, and 7, followed by the physics and engineering constraints on fusion reactors in Chaps. 8 and 9, respectively.

Chapter 1 displays interesting statistics on U.S. energy sources and world energy consumption rates, including the devastating atmospheric effects of CO_2 on the world climate. The historical development of magnetic confinement up to 1972 is also illustrated. Comparisons of similar energy pictures with the existing fission reactors also might have been very informative to the readers. Chapter 2 describes the basic kinetic theory and the concepts of plasma physics through which a particle distribution function is introduced. Note that the distribution function is to be defined in terms of the phase space, not just in a velocity space, as was done in Eq. (2-27). It also would be desirable to elaborate on the physical implications of the coulomb logarithm, which was really an arbitrary cutoff parameter, to make a converging plasma relaxation process.

Plasma confinement and transport are discussed in Chap. 3. Magnetic drift surfaces, various particle drifts including the radial drift, neoclassical diffusion, and the scaling laws are well presented in this chapter. A specific example with an $l = 2$ stellarator geometry is quite illustrative. This chapter is organized and explained very well. Perhaps more homework problems at the end of this chapter could have enhanced the material appreciation by the students. Chapter 4 analyzes the plasma equilibrium and instabilities, both on magnetohydrodynamics and microinstability. Discussion of the Bohr-Van Leeuwan theorem is an interesting addition to the subject of plasma equilibrium, which typical textbooks of this level often fail to mention. Description of the force-free plasma, however, needs more physical explanations rather than just the definition $\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} = 0$. On the treatment of microinstability, the two-beam plasma instability could have been expanded.

Plasma heating and refueling are discussed in Chap. 5. Plasma heating methods by ohmic, neutral beam (including fusion products), and radio-frequency heating are presented. In dealing with ohmic heating, it would be desirable to include discussions or a simple derivation on the plasma current limit (via the Kruskal-Shafranov limit). Also, the energy relaxation processes, when discussing neutral beam heating, should perhaps contain the energy loss mechanism, including the Rutherford differential cross section. Topics on compressional heating (e.g., the concept of the adiabatic toroidal compressor tokamak) are not discussed in this chapter, and the treatment of plasma refueling is rather limited. In Chap. 6, which relates to fusion reactions, note that the side reaction of deuterium-tritium (D-T) fuel yielding a $^5He + \gamma$ reaction would be only one part in 10^3 compared to an $n + {}^4He$ reaction; hence, the gamma energy would be very significant, posing some concern about the conventional shielding and diagnostic arrangements.

Chapter 7 describes the plasma particle and energy balance. When discussing Fick's law, it would be natural to add the physics of ambipolar diffusion. Note a word of caution about the terminology; "cyclotron" radiation is not the same physical phenomenon as "synchrotron" radiation, which is often confused to have the identical meaning. Incidentally, this chapter could use some homework problems. Chapters 8 and 9 lay out some physical and engineering constraints on fusion reactors. The Lawson criterion, with some examples for D-T and D-^{3}He plasmas, and illustrations of some operating regimes for wall loading, etc., for D-T and advanced fuel reactors are quite useful additions to these chapters.

Chapters 10 through 16, covering the last half (about 300 pages) of the book, discuss the various confinement concepts for toroidal and nontoroidal devices and topics on plasma engineering, including fusion power plant design studies. The history, characteristics, and physics of the tokamak are very well summarized in Chap. 10. This book is one of only a few textbooks that have good descriptions (in Chaps. 11 and 12) of alternate confinement concepts, including the reversed-field pinch, ohmically heated toroidal experiment (OHTE), toroidal magnetic cusps, topolotron, stellarators, torsatron, bumpi tori, heliac, tandem and multiple mirrors, cusp, surmac, theta and z pinches, imploding liner, Linus, astron, field-reversed mirror, spheromak, rotamak, plasma focus, and even Migma. Comparisons of various confinement concepts are summarized on Tables 11-5 and 12-1, which are quite informative. This represents the author's long research activities in the area of alternate confinement approaches.

Plasma engineering, reactor technology, and fusion reactor applications are covered in Chaps. 13, 14, and 15. Discussions of topics like direct energy conversion (in Chap. 13), neutronics, activation analysis, and displacements per atom analysis (in Chap. 14) might have been more in-depth. Chapter 16 completes the book by presenting fusion power plant design studies based on both the mainline D-T reactors (the MATT 1050 tokamak, the STARFIRE tokamak, and the Mirror Advanced Reactor Study) and the alternate concept reactors (the compact reversed-field pinch reactor, the OHTE, the Elmo Bumpy Torus reactor, etc.). However, only descriptive comparisons with tables and diagrams are presented. Nevertheless, these materials provide a good insight into the advantages and disadvantages of all concepts that are introduced.

Overall, this book is self-contained and provides a good basis and overview on various topics of fusion energy that are quite suitable for undergraduate students. The annotated bibliography at the end of the book is quite useful to students. As for revision, this current edition needs quite a bit of editorial touch, ranging from the index (e.g., "diamagnetism" is not even indexed) and a more unified set of homework problems to the quality of reproduced figures and diagrams. Often it is difficult to distinguish "8" from "B" in some of the figures. Also, the page numbers (e.g., pp. 102, 292, 328, etc.) are out of place. According to the *Chicago Manual of Style*, odd-numbered pages should begin on the right. Obvious typographical errors should be corrected in the next edition. My students mentioned to me jokingly that this book has a not-so-attractive appearance but that it is the best introductory fusion textbook they have come across so far. I would agree! For instructors, I would just like to add that the instructor's kit is available for this textbook.

Chan K. Choi is an associate professor of nuclear engineering at Purdue University. Previously, he served as the assistant director of the Fusion Studies Laboratory at the University of Illinois, Urbana-Champaign. He devotes much of his research efforts to theoretical and computational fusion plasma engineering, including studies of the charged-particle slowdown in fusion plasmas and advanced fuel inertial confinement fusion. He has edited two important conference proceedings, one on advanced fuel fusion (1977) and the other on fusion engineering (1981). He has also published more than 100 articles and technical reports.

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Victor L. Granatstein is a Professor of Electrical Engineering and Acting Director of the Laboratory for Plasma and Fusion Energy Studies at the University of Maryland. A member of the IEEE since 1960, Dr. Granatstein has held positions as Head of the High Power Electromagnetic Radiation Branch of the U.S. Naval Research Laboratory, and as Research Scientist for Bell Telephone Laboratories. He was Vice Chairman of the Executive Committee of the IEEE Nuclear and Plasma Science Society from 1984-1986, and was given the Navy Superior Civilian Service Award in 1980 and the R.D. Conrad Award for Scientific Achievement—presented by the Secretary of the Navy—in 1981.

Igor Alexeff is a Professor of Electrical and Computer Engineering at the University of Tennessee. Dr. Alexeff earned the Centennial Medal from the IEEE in 1984, and was awarded the title of Outstanding Engineer in the Southeast in 1987. In addition to having been Group Leader for the Oak Ridge National Labora- ries, Professor Alexeff is a ...

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Victor L. Granatstein and
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COLLISIONAL MAGNETIC PUMPING AS AN EFFICIENT WAY TO HEAT A PLASMA*

M. Laroussi and J. R. Roth
University of Tennessee, Knoxville, Tennessee 37996-2100

ABSTRACT

This paper describes the application of collisional magnetic pumping[1] to plasma heating. Theoretical solutions giving the heating rate for different magnetic field waveforms of the RF perturbing wave are presented. Numerical solutions to the energy transfer problem reveal a plasma parameter regime in which collisional magnetic pumping is most effective, and provide insight into the energy transfer mechanism. It is shown[2] that when the magnetic field waveform is a sawtooth function, the heating rate is proportional to the first power of the field modulation. This is an improvement over the case when a sinusoidal waveform is used, which results in second order heating. To implement experimentally the sawtooth waveform, a switching circuit using solid state power metal-oxide-semiconductor (TMOS) transistors was designed. The circuit is capable of driving a sawtooth shaped unidirectional current in the coil used to generate the RF magnetic field.

INTRODUCTION

Magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_o(1+\delta f(t))$, where B_o is the uniform steady-state background magnetic field, δ is the field modulation, and $f(t)$ is a periodic function. To achieve the collisional heating regime the following inequalities have to be satisfied

$$\tau_{ci} << \tau_{coll} \sim \tau_f << \tau_{tr}, \qquad (1)$$

where τ_{ci}, τ_{coll}, τ_f, and τ_{tr} are respectively the cyclotron period, the collision time, the period of the RF driving signal, and the transit time of the particles through the heating region. The equations governing the change in the parallel and perpendicular components of the energy of the particles are[1,3]

$$\frac{dE_\perp}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} - v_c\left(\frac{E_\perp}{2} - E_{11}\right) \qquad (2)$$

$$\frac{dE_{11}}{dt} = v_c\left(\frac{E_\perp}{2} - E_{11}\right) \qquad (3)$$

*Work supported by contract AFOSR 86-0100 (Roth).

Where v_c is the collision frequency. The above equations have been solved both analytically and numerically[2]. The analytical treatment provides the heating rate dE/dt for specific cases of the perturbing function f(t) and also provides the condition to be met if a heating rate proportional to the first power of the field modulation δ is to be achieved[2,4,5]. The numerical solutions provide additional information on the energy transfer process between the RF perturbed magnetic field and the parallel and perpendicular energy components of the heated species.

ANALYTICAL TREATMENT

When combined together, Equations (2) and (3) yield the following equation

$$\frac{d^2E}{dt^2} - \left[-\frac{3}{2}v_c + \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1} \right] \frac{dE}{dt} - \frac{v_c}{B}\frac{dB}{dt}E = 0 \qquad (4)$$

This is a second order differential equation with periodic coefficients. Such equations appear in astronomical and other applications where the stability and perturbations of periodic systems are at issue. The general solutions of these equations have been given by Floquet,[6] and have the following form

$$E = a_1 e^{\lambda t} p(t) \qquad (5)$$

Using a perturbation treatment and solving Equation (4) for the first power of δ, the factor ℓ_1 corresponding to this power in the expansion is found to be[4,5]

$$\ell_1 = \frac{v_c}{T}\int_0^T e^{\frac{3}{2}v_c s}\left\{ \frac{1}{1-\mathrm{Exp}\left(-\frac{3}{2}v_c T\right)} \int_0^T f'(u) e^{-\frac{3}{2}v_c u} du \right.$$

$$\left. - \int_0^s e^{-\frac{3}{2}v_c u} f'(u) du \right\} ds \qquad (6)$$

If $f(t) = \cos \omega t$, $\ell_1 = 0$ and Equation (4) has to be solved for the coefficient, ℓ_2, of the second power of δ. Carrying out this procedure yields the energy increase rate

$$\frac{dE}{dt} = \frac{\delta^2}{6}\frac{v_c \omega^2}{\frac{9}{4}v_c^2 + \omega^2}E_0 \qquad (7)$$

The above result agrees with the one found by Berger et al[1]. If the magnetic field assumes the profile shown in Fig. (1), the heating rate is of first order and is given by

$$\frac{dE}{dt} = \frac{\delta\omega}{3\pi} E_0 \tag{8}$$

Since $\delta << 1$, the above result can represent many orders of magnitude improvement on the preceding case.

NUMERICAL TREATMENT

Equations (2) and (3) have also been solved numerically. The magnetic field profile used for this analysis is shown in Fig. (2). The program has the flexibility of changing the slopes of the rising and decreasing ramps. An important variable is the collisionality parameter $v_c T$, defined as the dimensionless product of the collision frequency, v_c, and the period, T, of the RF signal. The time step chosen is 10^{-4}T. Fig. (3a) through Fig. (3d) show the plots of the parallel component of the energy and of the total energy of the particles versus time. The units on the energy axis are arbitrary, and on the time-axis are multiples of the period T. The field modulation for all cases is $\delta = 0.1$. As illustrated in Fig. (3b), when the collisionality parameter is less than 1, the plot of energy vs time doesn't show an increase with time in its average value. The explanation of this lies in Fig. (3a) which shows that after an initial transient phase the parallel component of the energy saturates and the magnetic pumping fails. As the collisionality parameter increases the saturation phenomena ceases and an increase in the average value of the total energy is obtained. This is illustrated in Fig. (3c) and Fig. (3d). Carrying out this analysis it is shown that there exists a threshold value of the collisionality parameter below which collisional magnetic pumping ceases to be effective. Also the energy transfer process through collisions is a resonant one where an optimum collisionality parameter exists at which the power absorption is maximized.

DESIGN IMPLICATIONS

The plasma on which the collisional magnetic pumping is to be tested is generated by a classical Penning discharge. The background uniform axial magnetic field can be varied up to 0.44 Tesla. The electron number density is typically $2 \times 10^9/cm^3$ in helium gas, with Te = 5- 10 ev. Fig. (4) is the schematic of the circuit to be used to generate the magnetic field waveform of Fig. (1). The inductor value is 1.6 μH. The circuit should be able to switch on and off a current of 100A at a frequency of several hundred KHz. The RF magnetic field generated is about 20 Gauss. The sudden change of the RF magnetic field from its maximum value to zero is not instanteneous however. Using state of the art TMOS transistors as switches a fall time of few hundreds of nanoseconds is possible. This slight distortion in the magnetic field waveform should not be a problem as long as the fall time is shorter than the collision time.

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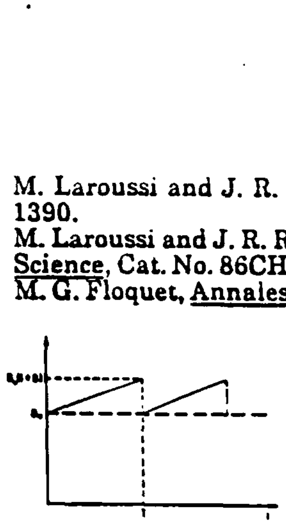


Fig. 1. Sawtooth waveform

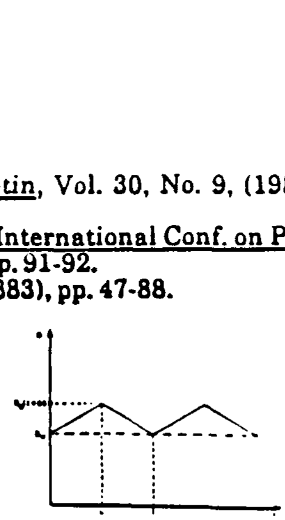
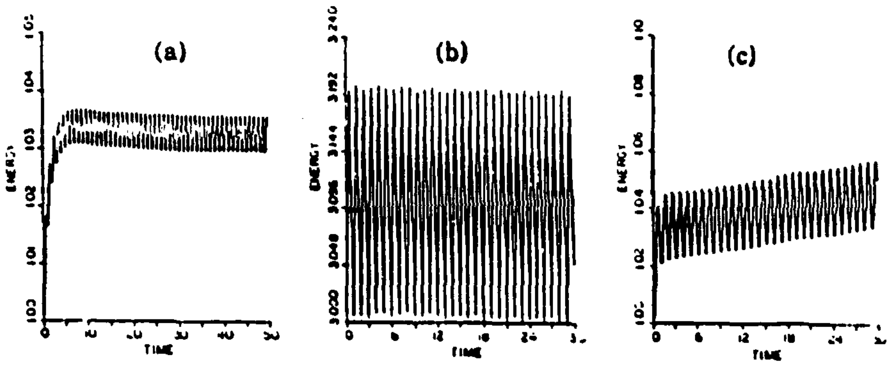


Fig. 2. Triangular waveform model used in the numerical treatment



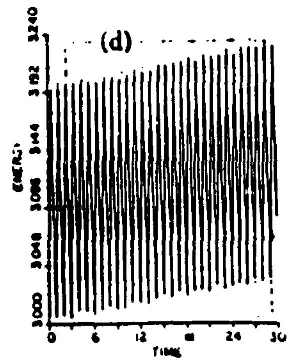


Fig. 3. (a) Parallel component of the energy vs time $\delta = 0.1$, $L = 0.5$, $v_c T = 0.5$.
(b) Total energy vs time $\delta = 0.1$, $L = 0.5$, $v_c T = 0.5$.
(c) Parallel component of the energy vs time $\delta = 0.1$, $L = 0.5$, $v_c T = 2$.
(d) Total energy vs time $\delta = 0.1$, $L = 0.5$, $v_c T = 2$.

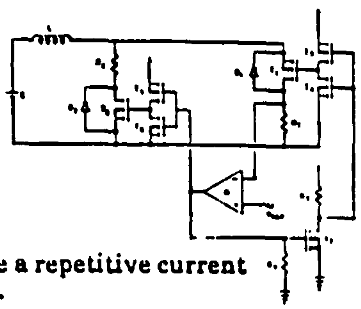


Fig. 4. Circuit used to generate a repetitive current ramp in the exciter coil.

MEASUREMENT OF THE EFFECTIVE MOMENTUM COLLISION FREQUENCY IN A TURBULENT, WEAKLY IONIZED PLASMA

J. Reece Roth and Paul D. Spence

UTK Plasma Science Laboratory

University of Tennessee, Knoxville, Tennessee 37996-2100, USA

Introduction

Electron cyclotron resonance absorbtion measurements have been made on a weakly ionized, steady-state, turbulent plasma using a Hewlett Packard 8510 Network Analyzer. This instrument is capable of swept frequency measurements of reflection and transmission coefficients from 0.045 to 18 GHz, with greater than 80dB dynamic range. The absorbtion measurements near electron cyclotron resonance are interpreted in terms of numerical solutions of the Appleton equation [1] to yield an "effective" collision frequency equal to the full width of the absorbtion curve at twice the resonance minimum. A two channel homodyne microwave scattering system (f_0 = 14 GHz) is used along with a capacitive probe to measure turbulence levels. Axial and radial Langmuir probes are used for electron number density and kinetic temperature measurements.

The Classical Penning discharge used to generate the plasma (see Figure 1) consists of a uniform magnetic field with a maximum value of 0.195 Tesla. The field is uniform to within 3% between anodes. An approximately 12 cm diameter steady state plasma column is generated which is 118 cm long. This plasma had a characteristic density of a few times 10^9 electrons/cm^3, electron kinetic temperatures of 10 eV to 100 eV, and helium ion kinetic temperatures of several hundred eV[2,3].

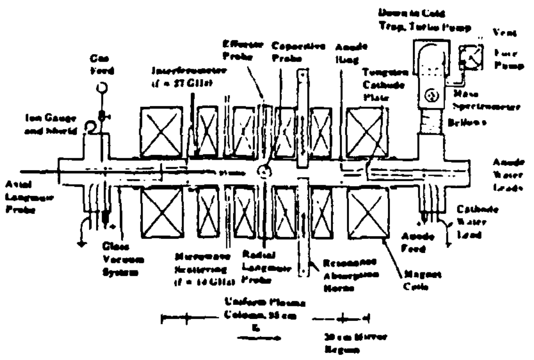


Figure 1 Plan View of Penning Discharge, with Diagnostic Equipment.

Measurements

Signals from the capacitive probe and the microwave scattering system were amplified and bandpass filtered. Both signals were processed by a Tektronix 7L5 spectrum analyzer. The turbulence spectrum power levels are measured using a Boonton model 91-12F RF detector. High pass filtering is 100kHz with low pass at 2 MHz. The apparatus was adjusted to try to maintain signal (power) levels at least 10 dB above the noise levels. The antenna geometry for the electron cyclotron resonance absorbtion measurements made on this plasma is shown in Figure 2 below,

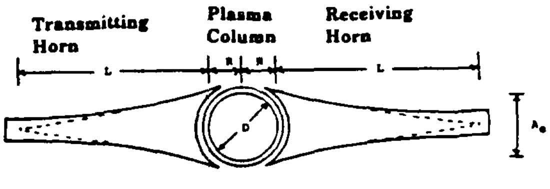


Figure 2 Cross-sectional view of Microwave Antenna Geometry for ECR Measurements in the Range 2-10 GHz. In this experiment, L = 34 cm, R = 6 cm, D = 12 cm, and A_g = 12 cm.

Figure 3 shows a characteristic absorbtion curve on the top, and the phase angle on the bottom. The sweep time for these traces is 500 msec with 10 traces averaged. It is desired that an electron remain in the beam sufficiently long to damp the absorbed energy by collisions rather than transport it out of the beam region by axial motion at the thermal velocity. For all data reported here, the product $\tau_e\, v_{eff} > 1$, implying that electrons made at least one collision while they were in the microwave probing beam.

The Effective Collision Frequency

The Appleton equation is a hydromagnetic equation relating a Lorentz collision term in a cold plasma to the propagation constants of an electromagnetic wave [1]. Numerical solutions to it were obtained for characteristic plasma conditions such as Figures 3; in general, it was found that the numerical solution had a resonance curve much narrower than the experimental data, and that the data often exhibited secondary absorbtion peaks or "plateaus" (like Figure 3) which were not predicted by the Appleton equation. This may be a non-linear mode coupling or a hot plasma effect.

Galeev and Sagdeev [4] introduce an effective collision frequency based on Langmuir turbulence (no magnetic field present);

$$v_s = \omega_{pe} \frac{W}{n_e T_e}, \qquad (1)$$

where W is the energy density of waves in the region of interest with wavelengths on the order of the Debye radius.

For drift wave turbulence Horton [4] derives the total fluctuation energy density

Roth, J. R. and Spence, P. D.: "Measurement of the Effective Momentum Collision Frequency in a Turbulent, Weakly Ionized Plasma". Proc. of the 18th International Conf. on Ionization Phenomena in Gases, Swansea, Wales, 13-17 July, 1987

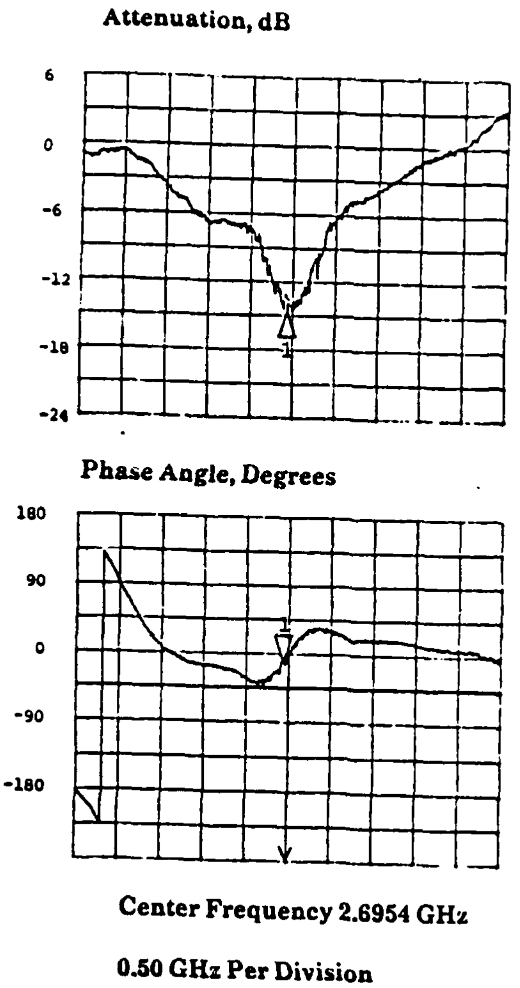


Figure 3 Electron cyclotron resonance absorbtion (top) and phase angle (bottom), for a maximum absorbtion at 2.689 GHz (triangle) and a full width at half maximum (3 dB above minimum) of v_{eff} = 47.5 MHz.

$$W = \sum_k W(k) = \frac{e^2 n_e}{2 T_e} \int dk \left| \phi(k)^2 + \left(\nabla_\perp \phi(k)\right)^2 \right| \qquad (2)$$

The capacitive probe will measure a function of $\phi(k)$ with the scattering power related to $\nabla_\perp \phi(k)$. Since neither the capacitive probe or the microwave scattering are absolutely calibrated, v_s is plotted in Figure 4 as a function of

$$v_s \sim \frac{n_e^{3/2}}{n_o T_e^2} P, \qquad (3)$$

where P is the integrated power spectra for either the capacitive probe spectra or the microwave scattering spectra, and n_0 is the neutral background density. Figure 4 indicates a disagreement of our data (v_{eff}) with the theory of Galeev and Sagadeev as elaborated by Horton [4] (v_s), since the data do not lie along a straight line with a 45° slope, showing a linear proportionality.

Conclusions

The measured effective collision frequency was consistently larger than the calculated electron-neutral collisional values, using the cross section at 10 eV. The effective collision frequency is as much as 20 times the binary, Lorentzian value. This increase in collision frequency is very probably due to electron scattering by plasma turbulence.

The use of a hydromagnetic equation avoids any Landau damping effects. However, two minima have been observed in the resonant absorbtion curves, indicating possible hot plasma effects (see Figure 3). The broad resonance curves and large phase shifts, as the double minima, indicate that a hydromagnetic treatment is not sufficient, although it does provide a good first approximation.

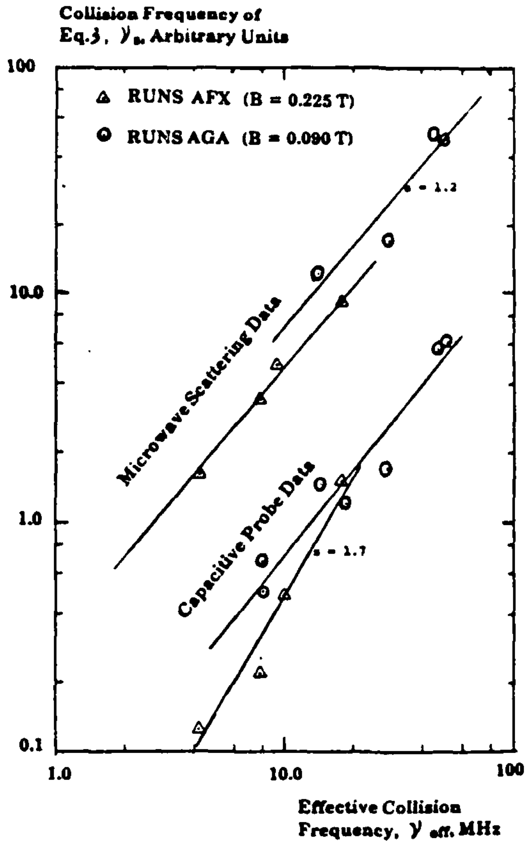


Figure 4 Collision frequency of Galeev and Sagdeev [4], v_s (Eq. 1) plotted against the effective collision frequency, v_{eff}, from ECR absorbtion measurements.

Acknowledgement

Experimental work supported by ONR Contract N00014-80-C-0063; Key equipment was supplied by AFOSR Grant 85-0152.

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PLASMA HEATING BY COLLISIONAL MAGNETIC PUMPING FOR POSSIBLE LOW PRESSURE INDUSTRIAL APPLICATION

By

J. Reece Roth and Mounir Laroussi

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100 U.S.A.

ABSTRACT

This paper describes some theoretical and experimental work on a previously neglected plasma heating technique, collisional magnetic pumping, and suggests how it may be used for industrial applications of plasmas at low pressure. Plasma heating by magnetic pumping is achieved by wrapping an exciter coil around a magnetically confined plasma. The confining magnetic field is then perturbed.

Theoretical solutions giving the heating rate for different magnetic field waveforms of the RF perturbing wave are presented. It is shown that when the amplitude of the magnetic field perturbation is a sawtooth function of time, the heating rate is proportional to the first power of the field modulation amplitude. This is an improvement over the case when a sinusoidal waveform is used, which results in second order heating. To implement experimentally the sawtooth waveform, a switching circuit using solid state power metal-oxide-semiconductor (TMOS) transistors was designed. The circuit is capable of driving a sawtooth shaped unidirectional current in the coil used to generate the RF magnetic field. Experimental measurements of the Q of the RF resonant circuit used to generate the sinewave perturbation will be presented, along with information which may be useful in applying this plasma heating method to high power industrial materials processing applications at sub-atmospheric pressures, where lack of electrode and wall contaminants in the plasma flow are particularly desirable.

INTRODUCTION

Magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_0(1+\delta f(t))$, where B_0 is the uniform steady-state background magnetic field, δ is the field modulation, and $f(t)$ is a periodic function. To achieve the collisional heating regime the following inequalities have to be satisfied

$$\tau_{ci} << \tau_{coll} \sim \tau_f << \tau_{tr}, \qquad (1)$$

where τ_{ci}, τ_{coll}, τ_f, and τ_{tr} are respectively the cyclotron period, the charged particle collision time, the period of the RF driving signal, and the transit time of the particles through the heating region. The equations governing the change in the parallel and perpendicular components of the energy of the particles are[1-3]

Presented at the 8th International Symposium on Plasma Chemistry, Tokyo, Japan August 31-September 4, 1987. Supported by contract AFOSR 86-0100 (Roth).

$$\frac{dE_\perp}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} - v_c\left(\frac{E_\perp}{2} - E_{11}\right) \tag{2}$$

$$\frac{dE_{11}}{dt} = v_c\left(\frac{E_\perp}{2} - E_{11}\right) \tag{3}$$

Where v_c is the collision frequency. The above equations have been solved both analytically and numerically[2]. The analytical treatment provides the heating rate dE/dt for specific cases of the perturbing function f(t) and also provides the condition to be met if a heating rate proportional to the first power of the field modulation δ is to be achieved[2,4,5]. The numerical solutions provide additional information on the energy transfer process between the RF perturbed magnetic field and the parallel and perpendicular energy components of the heated species.

ANALYTICAL TREATMENT

When combined, Equations (2) and (3) yield the following equation[2,3]

$$\frac{d^2E}{dt^2} - \left[\frac{3}{2}v_c + \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right]\frac{dE}{dt} - \frac{v_c}{B}\frac{dB}{dt}E = o \tag{4}$$

This is a second order differential equation with periodic coefficients. Such equations appear in astronomical and other applications where the stability and perturbations of periodic systems are at issue. The general solutions of these equations have been given by Floquet,[6] and have the following form

$$E = a_1 e^{\lambda t} p(t) \tag{5}$$

Using a perturbation treatment and solving Equation (4) for the first power of δ, the factor ℓ_1 which is its coefficient in the expansion of E(t) is found to be[4,5]

$$\ell_1 = \frac{v_c}{T}\int_0^T e^{\frac{3}{2}v_c s}\left\{\frac{1}{1-\mathrm{Exp}(-\frac{3}{2}v_c T)}\int_0^T f'(u)e^{-\frac{3}{2}v_c u}du\right.$$

$$\left. - \int_0^s e^{-\frac{3}{2}v_c u} f'(u)du\right\}ds. \tag{6}$$

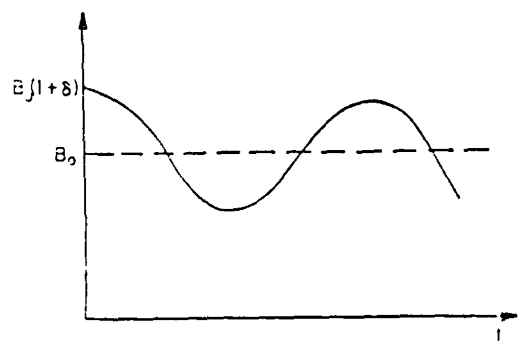

Fig. (1a). Sinusoidal waveform.

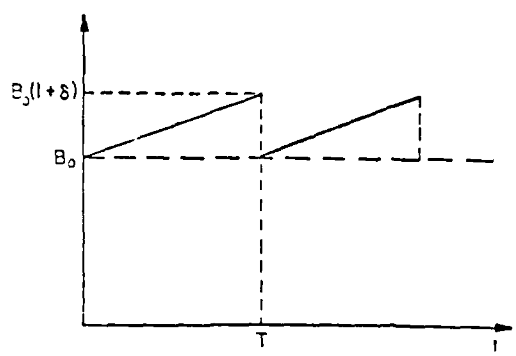

Fig. (1b). Sawtooth waveform.

If $f(t) = \cos \omega t$, as shown schematically in Fig. (1a), $\ell_1 = 0$ and Equation (4) has to be solved for the coefficient, ℓ_2, of the second power of δ. Carrying out this procedure yields the energy increase rate

$$\frac{dE}{dt} = \frac{\delta^2}{6} \frac{\nu_c \omega^2}{\frac{9}{4}\nu_c^2 + \omega^2} E_0 \tag{7}$$

The above result agrees with the one found by Berger et al[1]. If the magnetic field assumes the profile shown in Fig. (1b), the heating rate is of first order and is given by

$$\frac{dE}{dt} = \frac{\delta\omega}{3\pi} E_0 \tag{8}$$

Since $\delta << 1$, the above result can represent many orders of magnitude improvement on the preceding case.

NUMERICAL TREATMENT

Equations (2) and (3) have also been solved numerically. The magnetic field profiles used for this analysis are shown in Fig. (1a) and (1b). An important variable is

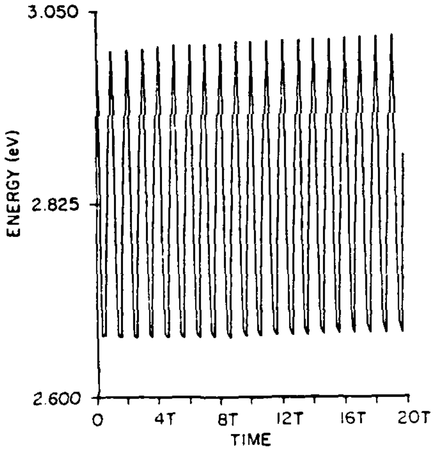

Fig. (2a). Total energy versus time for $\delta = 0.1$, $\nu_c T = 0.2$ and a sinewave perturbation.

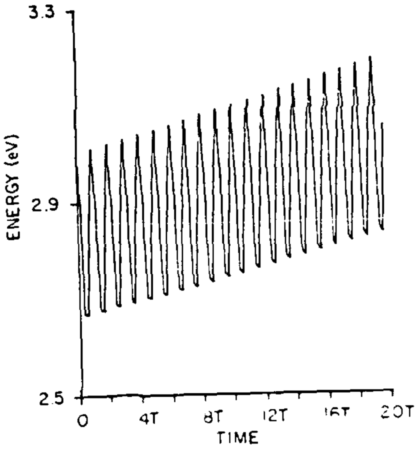

Fig. (2b). Total energy versus time for $\delta = 0.1$, $\nu_c T = 6$, and a sinewave perturbation.

the collisionality parameter $\nu_c T$, defined as the dimensionless product of the collision frequency, ν_c, and the period, T, of the RF field. Fig. (2a) and Fig. (2b) are the plots of the total energy of the charged particles versus time, when a sinewave is used as the field perturbation. Fig. (2a) is for a collisionality parameter of 0.2. This means that there are 2 collisions per 10 cycles. In this relatively collisionless case the average value of the energy shows little increase in time. In contrast, Fig. (2b) is for a collisionality parameter of 6. This means there are 6 collisions per cycle. In this relatively highly collisional case, the average value of the energy shows a definite increase in time. Fig. (3a) and Fig. (3b) are the plots of the total energy of the charged particles versus time

when a sawtooth perturbation is used. In this case the energy increases linearly with time and does not depend on the collisionality parameter.

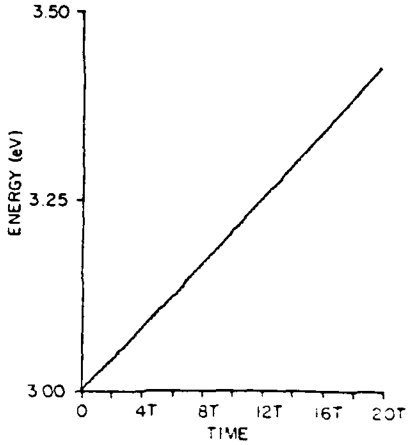

Fig. (3a). Total energy versus time for $\delta = 0.01$, $v_c T = 0.2$, and a sawtooth perturbation.

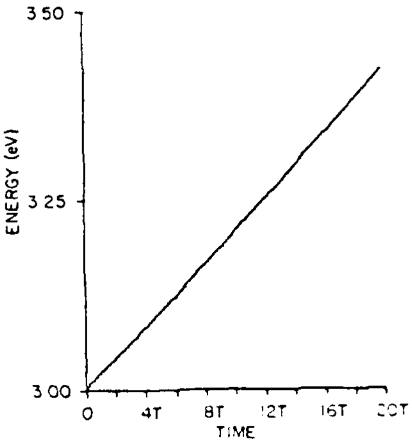

Fig. (3b). Total energy versus time for $\delta = 0.01$, $v_c T = 6$, and a sawtooth perturbation.

The heating rate has been plotted against the collisionality parameter for both sinusoidal and sawtooth waveforms. Fig. (4a) shows that in the case when a sinewave is used there exists an optimum value of the collisionality parameter at which the heating rate is a maximum. On the other hand, Fig. (4b) shows that the heating rate is independent of the collisionality parameter when a sawtooth waveform is used. Note that both figures contain the analytical results obtained by using Equation (7) and

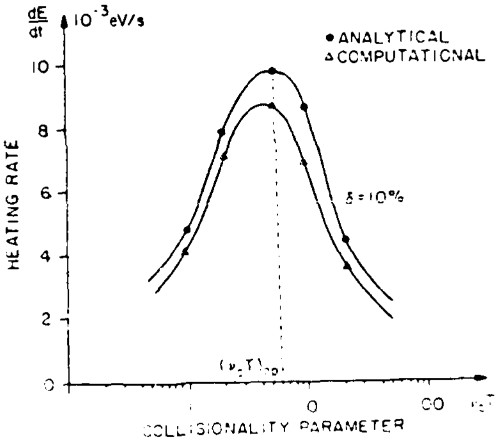

Fig (4a). Heating rate versus collisionality parameter, $v_c T$, for $\delta = 0.1$ and a sinewave perturbation.

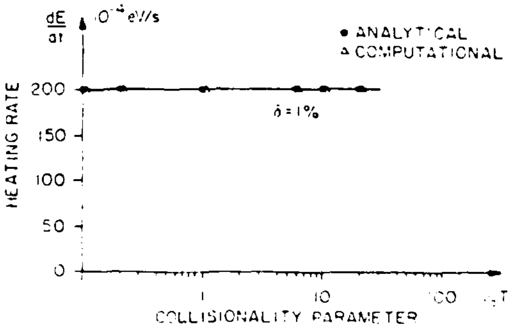

Fig. (4b). Heating rate versus collisionality parameter, $v_c T$, for $\delta = 0.01$ and a sawtooth perturbation.

Equation (8) respectively, and the computational results obtained by a numerical solution to Equations (2) and (3). The absolute values of the heating rates in Figs. (4a) and (4b) suggest that for the same value of the field modulations, δ, the sawtooth heating would be several hundred times faster than heating with a sinusoidal waveform.

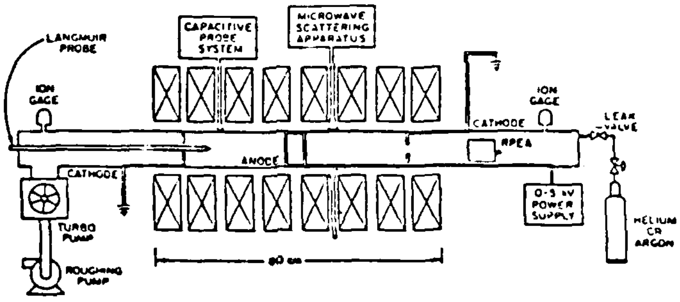

Fig. (5). The classical Penning discharge.

DESIGN IMPLICATIONS

The plasma on which the collisional magnetic pumping is to be tested is generated by a classical Penning discharge[7,8]. The background uniform axial magnetic field can be varied up to 0.44 Tesla. The electron number density is typically 2 x $10^9/cm^3$ in helium gas, with T_e = 5-10ev. Fig. (5) is a schematic of the apparatus. Fig. (6a) is a block diagram of the circuit used to achieve a high Q resonant circuit. This circuit is driven and analyzed by a network analyzer. The latter furnishes the plot of the impedance of the high Q circuit versus frequency. From this plot the value of Q and of the amplitude of the impedance at resonance can be computed. Fig. (7) is the plot of the logarithmic amplitude of the impedance of the circuit versus frequency. The Q in this case is 350. Fig (6b) is the schematic of the circuit used to generate the magnetic field waveform of

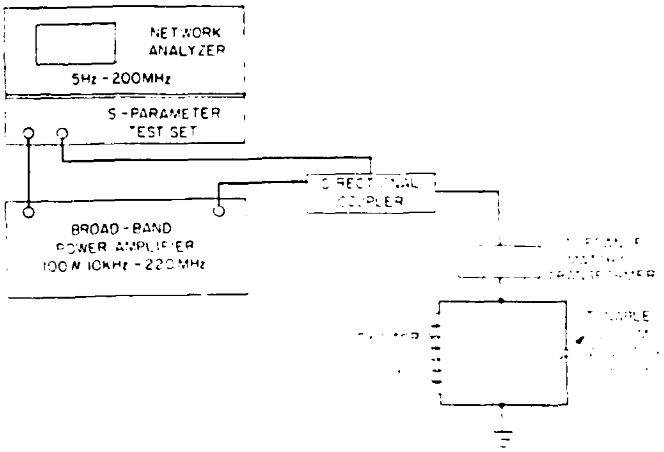

Fig. (6a). Experimental setup to drive and analyze the high Q circuit.

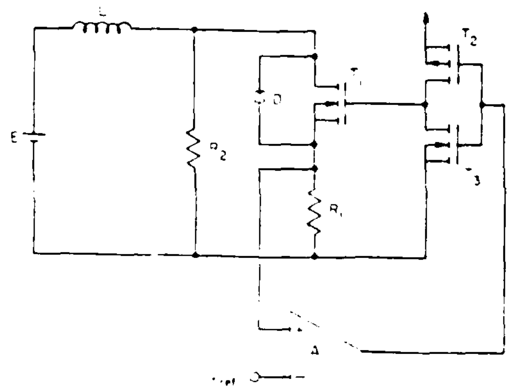

Fig. (6b). Circuit used to generate a repetitive current ramp in the exciter coil.

Fig. (1b). The circuit should be able to switch on and off a current up to 100A at a frequency of several hundred KHz. The amplitude of the RF magnetic field for a coil of 2 μH can reach up to 2 x 10^{-3} tesla. The sudden change of the RF magnetic field from its maximum value to zero is not instantaneous however. Using state-of-the-art TMOS transistors as switches a fall time of few hundreds of nanoseconds is possible. This slight distortion in the magnetic field waveform should not be a problem as long as the fall time is shorter than the collision time.

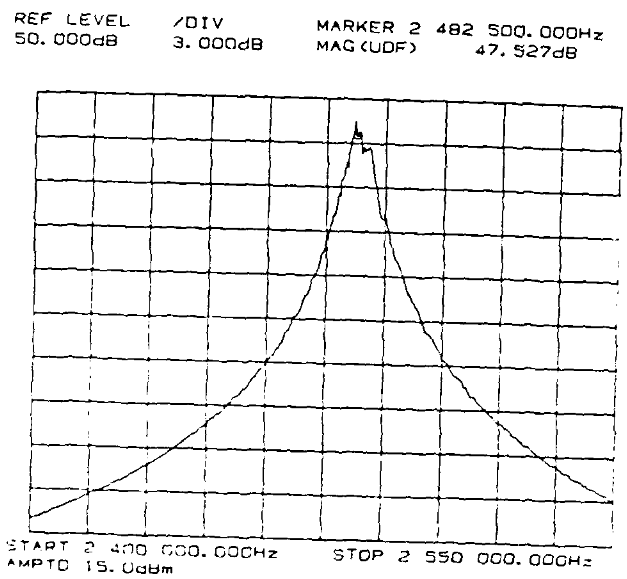

Fig. (7). Logarithmic amplitude of the impedance of the resonant circuit versus frequency.

DISCUSSION

There are many requirements for plasma heating in the field of materials processing. In the past, collisional magnetic pumping has not been considered for these applications because the heating rates obtainable by sinusoidal RF waveforms, given by Equation (7), are factors of ten smaller than other competitive RF heating methods such as ion cyclotron resonance heating (ICRH) or DC arcs. However, the first order collisional magnetic heating given by Equation (8), which results from the sawtooth waveform of Fig. (1b), is several factors of ten larger than that of Equation (7), and is comparable with that of ICRH under characteristic low-pressure operating conditions. Such high heating rates may find applications to low pressure materials processing, where energetic electrodeless, contamination-free plasmas are required.

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Chapter 8
THE ORBITRON MICROWAVE MAS?R

Igor Alexeff

University of Tennessee
Knoxville, Tennessee

8.1 INTRODUCTION*

The *orbitron microwave maser* is an extremely simple and compact device that produces power in the difficult submillimeter and millimeter wavelength regions. In its most simple form, the orbitron maser comprises a central positive wire placed inside a microwave cavity. Electrons, which are confined electrostatically in orbits around the wire, couple to cavity modes and radiate. Because the wire can be made quite thin, electrons close to its surface are in a high electrostatic field, orbit at a high frequency, and emit very-high-frequency radiation. The instability driving the emission is quite strong because electrons trapped in a logarithmic potential well around a wire are negative-mass unstable [1]. Two typical models, along with a pen for size, are shown in Figure 8.1.

Two advantages of the orbitron maser over other advanced microwave tubes, such as the gyrotron and free-electron laser, are that the orbitron does not require a high magnetic field to produce submillimeter microwave radiation. The orbitron maser does not use any magnetic field and it does not require relativistic electrons to cause the negative-mass instability as in magnetic devices, such as the gyrotron.

The orbitron maser has caused much interest in microwave laboratories around the world. In addition to the original work at the University of Tennessee, orbitrons have been studied at the Hughes Research Laboratories, NRL, Grinnell College, in Israel, and in laboratories in the

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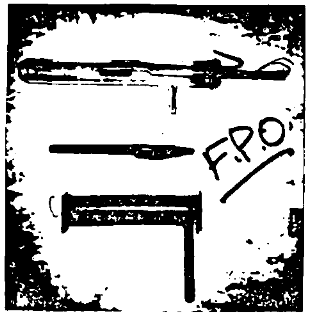

Fig. 8.1 Typical Orbitron Maser Designs
Note: The upper device is the one with which the radiation at 1 THz was generated. The lower device has plastic windows at both ends, and was used for plasma density measurements with an externally generated probe signal. Both are gas-filled, pulsed devices. A fountain pen is used for size information.

People's Republic of China. The simplicity of the device, and the extremely high frequencies produced (1 THz) suggest that orbitron masers will have a niche in the microwave world of the future.

8.2 BASIC PHILOSOPHY

The basic concept in the design of the orbitron maser was to create a very-high-frequency microwave device by combining the most appropriate features of lasers with those of conventional microwave vacuum tubes. In this respect, the orbitron maser is intended to bridge the gap between microwave tubes and lasers. Thus, instead of electron beams, the concept was created to use electrons orbiting around positive wires, in analogy to electrons orbiting positive nuclei, to produce a lasing medium. These orbits can be so small that very high frequencies can be obtained without such heroic measures as frequency upshifts by relativistic electron beams. To obtain more power, many wires could be placed in the cavity to form a lasing medium locked in phase by a common microwave field.

Another laser concept is to use cavity resonators instead of discrete traveling wave structures [2]. The problem with discrete structures is that, for very high frequencies, the structures become very small, difficult to fabricate, and hard to cool. Cavity resonators can be overmoded, and hence quite large and easy to cool. However, frequency selection can still be obtained by properly treating the cavity wall. For example, the wall could be composed of an interference filter, in analogy with the multilayer dielectric filters used at the ends of laser tubes.

One advantage of using a medium of electrons orbiting positively charged wires is that the electron orbits in the logarithmic potential well are negative-mass unstable. In other words, the electron cloud tends spontaneously to bunch in azimuth, and consequently to radiate collectively. In fact, in the orbitron pressure gauge tube [3] of Professor R. G. Herb, the instability is apparently spontaneous in the absence of a cavity resonator and limits the low-pressure performance of the gauge [4].

To improve the performance of our orbitron masers at high frequency, we have etched our wires to produce alternate thick and thin sections. Computer simulation demonstrates that the electrons are trapped around the thicker wire sections, in analogy to electrons being trapped around positive nuclei in the atoms used in lasers [5]. In this case, we consider the device to most closely resemble a radio frequency laser, or maser.

Very high potentials and electric fields can be used in the device, because the central wire is positive, and electron field-emission cannot occur. In addition, due to the logarithmic nature of the potential well, the high field region is limited in volume.

8.3 EARLY EXPERIMENTS AND THEORY

The concepts used in the orbitron microwave maser grew out of the author's early experiences in the nuclear research laboratory of Professor R. G. Herb at the University of Wisconsin. There, I worked on the *evaporion vacuum pump*, in which chemically active gases were gettered by evaporated titanium. Chemically inert gases, such as argon, were ionized by an electron beam, then electrostatically driven into the titanium-coated wall [6]. One model of the pump gave remarkably good performance with argon. Subsequently, the good performance was found to be due to intense argon ionization caused by electrons orbiting an anode of fine, parallel wires. The success of this pump led Professor Herb to extend the principle to a new form of ultra-high-vacuum gauge, which was subsequently marketed [3].

The basic concept of the trapping of electrons around a positive wire remained with the author, and I subsequently applied it to a fast-opening

plasma switch, which I patented [7]. I also noted that the orbiting frequencies of electrons confined about thin wires at moderate potentials could be very high, so an orbitron microwave maser could be very useful. A simple theoretical model, using a resistive wall, instead of a reactive cavity resonator, was worked out while on an airplane trip from Knoxville to Santa Barbara, CA, and the experimental program thus started [1].

Early experiments succeeded with the excellent experimental help of Fred Dyer of the University of Tennessee. The experimental observation of intense microwave emission with wavelengths between 3 cm and 5.5 mm from a pulsed, gas-filled tube, along with the primitive resistive-wall theory, were published in *Physical Review Letters* [1]. In addition, a US patent application on the principle was filed, and subsequently granted [8].

The basic configuration used in these early experiments is shown in Figure 8.1. A low-pressure gas environment (about 20 μm) was provided by a bell-jar equipped vacuum system, as shown in Figure 8.2. A thin tungsten wire was the anode (typically 20 mils in diameter). An empty beer can served the three functions of cavity resonator, discharge cathode, and axial confinement of electrons by means of the negative ends. A high-voltage pulsed power supply (600–30,000 V) was provided by a capacitor in series with a spark gap. The sequence of operations was as follows. First, the spark gap fired. Then, a discharge built up in the orbitron maser. After a delay time that was inversely proportional to pressure (typically 10 μs), a microwave pulse was emitted. The power levels observed were typically several watts. Finally, the device changed to a low-voltage, nonemitting mode. Because the microwave emission occurs after the spark gap fires, the microwave emission does not come from the spark gap. This conclusion is verified by localizing the emission with microwave horns. Also, the spark gap does not emit substantial power at frequencies above about 10 GHz.

The basic equation giving the highest possible fundamental frequency for circular orbits is given below:

$$f = \frac{1}{2\pi r}\left[\frac{-ZeV}{m\ln(R/r')}\right]^{1/2} \qquad (8.1)$$

where f is the emitted frequency (Hz), Z and e are the sign and charge of an electron (1.60×10^{-19} C), V is the potential applied to the central wire (V), r is the radius of the electron orbit (m), m is the mass of an electron (0.91×10^{-30} kg), ln is the natural logarithm, R is the radius of the outer electrode or cavity resonator (m), and r' is the radius of the wire (m). For the highest emitted frequency, the electrons must have the smallest possible orbit, or $r = r'$. For a wire of one mil (25 μm) in diameter inside a cavity resonator of one inch (2.54 cm) in diameter and an applied voltage of 30 kV, the predicted maximum frequency is 3.5^{11} Hz, corresponding to a wavelength of 0.85 mm. These values are typical for operating devices that have been constructed, and the predicted frequency limit is approached and often attained, thus supporting the model. Harmonic production can exceed this limit, as may electron space-charge effects (by, in effect, reducing the outer radius R).

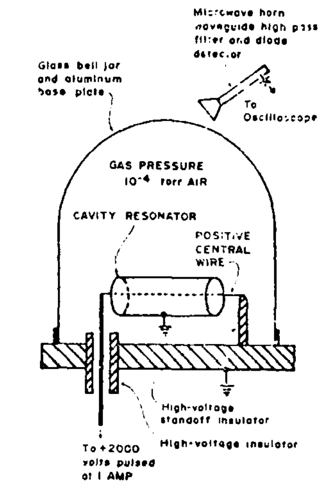

Fig. 8.2 The Original Orbitron Maser Configuration Inside a Bell Jar

Note that (8.1) predicts that the frequency f increases as energy is removed from an electron and it sinks deeper into the potential well around the wire (r decreases). Such an increase of frequency as energy is decreased is referred to as a *negative-mass* effect. It cannot occur in linear systems, only in circular ones. Such a system can be shown to be inherently unstable (See the references at the end of this chapter.)

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A verification of the orbitron theory is discussed in the cited paper [1]. The idea is that the highest emitted fundamental frequency is given by simple orbit theory (8.1). The highest fundamental is proportional to the square root of the applied voltage. The results presented in this early paper are shown in Figure 8.3, and show how higher frequencies require higher voltages. One further interesting observation was that a very weak magnetic field (a few gauss) turned off the microwave emission, although the field had no other observed effect on the discharge. Figure 8.4 shows the effect of an axial magnetic field on microwave emmission.

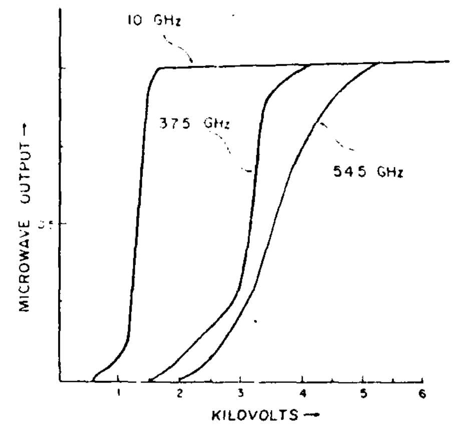

Fig. 8.3 Observed Upper Frequency Increase with Increasing Voltage

An attempt to demonstrate maser amplification with this same apparatus appeared to be successful. A 3 cm microwave signal was introduced into the side of the cavity. When the orbitron power pulse was reduced below some well defined threshold, microwave emission did not appear, unless the 3 cm signal was present. The defect in the experiment was that it was done with microwave diodes and horns, however, and the narrow-band nature of the apparently amplified signal could not be verified.

The decision was made to progress as rapidly as possible to higher frequencies because the orbitron maser could outperform other devices at

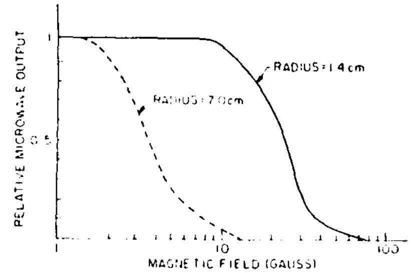

Fig. 8.4 Observed Reduction of Microwave Emission with Increasing Axial Magnetic Field

Note: The two curves are for different radii of the cavity resonator.

that range. The first barrier was the inability of the device to produce wavelengths shorter than 5.5 mm. One possible limitation was that the very high frequencies were being produced by electron orbits too close to the wire. Such orbits are not affected by the confining electric field of the end plates, escape axially through the holes in the end plates, and do not participate in the maser action. A way of overcoming this limitation was to etch grooves in the central wire, which produced an axial electrostatic confining field, as shown in Figure 8.5. In effect, the wire has been converted into a chain of positive nuclei. Computer simulation demonstrated the effectiveness of this axial confinement [5], and in experiments the orbitron maser produced wavelengths down to 2 mm.

For wavelengths shorter than 2 mm, the limitations were in the diagnostic devices, rather than in the orbitron maser. Eventually, an indium antimode crystal detector, operating at liquid helium temperatures, was obtained and debugged. The radiation was focused by plastic lenses, and the frequencies were determined by transmitting the radiation through many layers of fine wire mesh. By using these techniques, orbitrons with very fine wires (less than $\frac{1}{2}$ mil or $\frac{1}{80}$ mm in diameter), as shown in Figure 8.1 (top), and very high voltages (30,000 V), radiation was observed at $\frac{1}{3}$ mm wavelength, or 1 THz [9]. The power at 1 THz was about 1 W. This emission is considerably higher in frequency and in power than that produced by devices of comparable simplicity.

Fig 8.4

Positive Wire

Cavity
(Beer Can)

Electron Orbit Electric Field Original Maser (a)

Etched Positive Wire Open Cavity Electron Orbit Electric Field Improved Maser (b)

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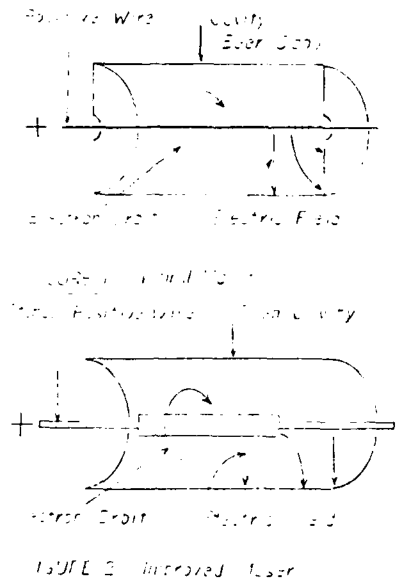

Fig. 8.5 Modifications in the Electric Field Around a Wire Caused by Etching

One problem with using wire meshes for frequency determination is that wire meshes do not have a sharp transmission cut-off with decreasing frequency. These difficulties have led us to develop some new and superior devices, which, unfortunately, are proprietary at the time of this book's publication (*circa* 1987).

8.4 RECENT EXPERIMENTS AND THEORY

Recent orbitron maser experiments have concentrated on two areas: first, the production of high-vacuum, steady-state devices; second, a demonstration that the emission of microwave radiation from the gas-filled, pulsed devices is due to orbiting electrons, rather than plasma oscillations.

The first operation of steady-state, high vacuum orbitron masers was accomplished with the able help of Mark Rader. The devices were very simple systems to which an oxide-coated cathode was added in the form of a wire parallel to the central wire. The success of the experiment was due to having a very sensitive Hewlett-Packard panoramic receiver on hand, so that the low level radiation from an unoptimized orbitron could be detected and increased by appropriate adjustments. Line radiation was observed at applied voltages of about 1 kV and at currents of a few milliamperes. The highest frequency emitted was close to that predicted by simple theory for circular orbits just grazing the wire anode (differing by a factor of between $\frac{1}{4}$ and 1). Because the device suffered from space-charge limitation of electron flow, multiple wires were tried in order to obtain more current. The orbiting electron clouds around each wire were expected to phase-lock to the common radiation field in the cavity. These experiments appeared to be successful, as the power output and highest frequency emitted increased as the number of wires was increased from one to seven. The highest frequency emitted in the steady state so far is about 10 GHz, the limitation being the overheating of the device when the voltage is increased to produce higher frequency. The use of many anode wires to share the heat load is anticipated to remove the frequency limitation.

The gas-filled, pulsed orbitron maser tubes are useful because high voltages can be applied for short times to produce extremely high frequencies without overheating. The gas is necessary for the production of ions to reduce electron space charge. This permits the higher electron currents, which appear necessary to obtain very-high-frequency emission. Some authors have stated that the operation of the gas-filled devices has nothing to do with orbiting electrons, but is caused by the emission by plasma oscillations (at the second harmonic) from the plasma produced by the gas [10]. For the observed emission at 1 *THz* this explanation appears unlikely because the plasma frequency in the device would be considerably lower, even if the gas were 100% ionized. However, the experiments described below were done at lower frequencies to check the plasma hypothesis.

The most obvious way of checking an orbitron maser to observe the occurrence of plasma emission is to check directly the radio-frequency properties of the plasma itself [11]. Consequently, several devices were constructed in which the cavity resonator was also a piece of waveguide. A steady-state, externally produced radio-frequency signal was sent through the waveguide, while the waveguide was also operated as an orbitron maser, as shown by the bottom device in Figure 8.1. The object

was to determine the plasma frequency in the orbitron maser during and after orbitron emission by observing the cut-off of the external signal by the plasma filling the device. The results were quite clear: under appropriate operating conditions, the externally generated frequency penetrated the plasma, while the orbitron was emitting a frequency over four times higher. Thus, plasma oscillations were not responsible for microwave emission in these cases. A cross-check with a Langmuir probe, which is used to measure plasma density, verified that it was too low to cause the observed emission. However, under other conditions (higher gas pressure or lower orbitron frequency), the externally transmitted signal was indeed cut off, and, in this case, the result was ambiguous.

A surprising discovery was that more resonant systems existed other than the empty cavity resonator. Line emission was found corresponding to resonances of the coaxial system formed by the cavity resonator with the central wire. Low-frequency lines were observed, which corresponded to the external circuitry supplying power to the device. A low-frequency line was found in steady-state experiments with gas filled tubes, which corresponded to the excitation of background plasma in the device. This low-frequency line was tuned by changing the background plasma density. Thus, the powerful negative-mass instability of the orbiting electrons couples to whatever resonant system is available.

Our theoretical advances clearly show the negative-mass instability to be present. The advances include a treatment of the orbitron maser for circular orbits that predicts enhanced emission at harmonics of the orbit frequency [12], a Vlasov treatment of an electron cloud with a distribution in energy that predicts emission slightly above the frequency of the interacting, orbiting electrons [13], a treatment of noncircular orbits that shows enhanced emission at harmonics [14], an electrostatic analog of the loss cone for particles confined in a magnetic mirror [15], and a magnetically coupled system in addition to the original, electrostatically coupled one [16]. Computer simulation has also been used successfully, in particular, in demonstrating the enhanced confinement of orbiting electrons around a multiply etched wire [5].

8.5 SUMMARY OF RECENT ORBITRON WORK AT OTHER LABORATORIES

The first group outside of ours to become interested in the orbitron was the Hughes Research Laboratory at Malibu, CA. Under the direction of Jay Hyman, work was initiated by Jay Palmer. The attempts to produce operating orbitrons were unsuccessful, and so the group purchased two units from the University of Tennessee. The work was extended by Robert Schumacher and Robin Harvey, who came to the conclusion that the observed emission in the gas-filled orbitron was due solely to plasma oscillations [10]. The Hughes researchers were also unable to obtain emission from a hot-cathode-equipped vacuum orbitron.

Next, Bill Case from Grinnell College also became interested. With help from our group at Tennessee, he produced an operating device and studied the mode structure inside the cavity resonator [17].

The Naval Research Laboratory in Washington, DC became very interested, and has done a comprehensive study in analytic theory and computer simulation. First, Y. Y. Lau observed from work originating in analytic and computer studies of relativistic betatrons that the orbitron configuration (radially outward electric field, no magnetic field) was the most unstable configuration of those under study [18]. Therefore, this configuration was very good for the production of microwave radiation. A comprehensive analytical study was carried on by Manheimer, who investigated highly eccentric orbits around the wire, and showed that strong emission occurred at harmonics of the periodic orbit frequency [19]. Ganguli led a comprehensive computer study of the saturation mechanism and efficiency of power production for a beam-driven orbitron. The conclusion was that the possible efficiency was low compared with other devices such as gyrotrons [20].

Yacob Ben-Aryeh in Israel was interested in the possibility that orbitron emission was related to an electron-gas atom collisional process that he had been studying [21]. He visited the University of Tennessee, conducted experiments there, and took an orbitron back to Israel. Subsequently, the device was reported to be operational.

Liu Shenggang, the President of the Chengdu Institute of Radio Engineering, the People's Republic of China, spent several weeks visiting the University of Tennessee, experimenting with orbitrons, and giving lectures. He reports that there is a large program for constructing and studying orbitrons at Chengdu, and that the basic concepts have been extended to new types of hybrid devices [22].

8.6 FUTURE PROSPECTS

The basic experimental work on orbitron microwave masers at the University of Tennessee, plus the generally favorable reception elsewhere, suggest that there is a real need for the device. The reason is that it can produce reasonable amounts of microwave radiation in the difficult gap in

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the electromagnetic spectrum between microwaves and light. In addition, the device is quite simple, small in size, easy to fabricate, and reliable.

Applications for such a device are numerous, such as high resolution radar, compact radar (small antenna structures), secure radar (not detectable at long ranges due to atmospheric absorption), broadband communication systems (due to the high frequency), and basic research (easy access to a new frequency range).

The goals of our program at the University of Tennessee include producing still higher frequencies and constructing a steady-state orbitron maser of moderate power. We believe that multiple-anode systems, analogous to a laser with a large lasing volume, will prove to be very useful. The progress has been slower than desired because we not only have to develop the microwave emitter, but also the frequency measuring and detecting systems at the same time.

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Electron Density and Temperature in the Pulsed-Orbitron-Maser Glow Discharge

MARK RADER, FRED DYER, AND IGOR ALEXEFF, FELLOW, IEEE

Abstract—In order to better understand the pulsed-glow discharge that provides the feed electrons for our pulsed-orbitron maser, we have been using penetrating microwave beams and radially inserted Langmuir probes to make bulk and radial measurements of the number density in the plasma. We have also used the Langmuir probe to measure the electron temperature across the plasma radius, and we investigated the effects of an externally applied magnetic field on the RF output of the orbitron. We have found that the emitted frequency is apparently not related to the electron plasma frequency by any simple linear relationship, and that an externally imposed magnetic field of as little as 70 G is required to kill the instability.

I. Introduction to the Orbitron Maser

THE ORBITRON MASER is a coaxial device which utilizes negative mass unstable electrons orbiting around a central wire to produce RF radiation [1]. Electrons are supplied to the device by either a hot oxide-coated tungsten filament for steady-state operation [2] or by a glow discharge for operation in a pulsed mode [1]. The configurations for pulsed and steady-state operation are shown schematically in Fig. 1. Since there is a positive central anode wire, the electrons from the electron source are trapped in a logarithmic electrostatic potential well. In this type of rotating system, the electrons are naturally negative mass unstable and so as they spiral into the central wire they produce RF radiation.

We have been exploring the conditions inside the pulsed maser so as to determine the bulk average number density and also to show how the number density varies with the plasma radius near the central wire. We have also determined the radial profile of the electron temperature and the effects that externally applied axial and transverse magnetic fields have on the RF output of the device.

II. Diagnostic Methods

There were two methods used to determine the bulk and the radial profile data. The first method utilized a microwave beam, which was passed along the coaxial cavity of the orbitron maser. The second method of diagnostics was a conventional Langmuir probe, which was inserted radially and could be repositioned radially across the diameter of the discharge. We also used a uniform magnetic field to determine the effects of magnetic field on the RF output.

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The authors are with the Electrical Engineering Department, University of Tennessee, Knoxville, TN 37996-2100.

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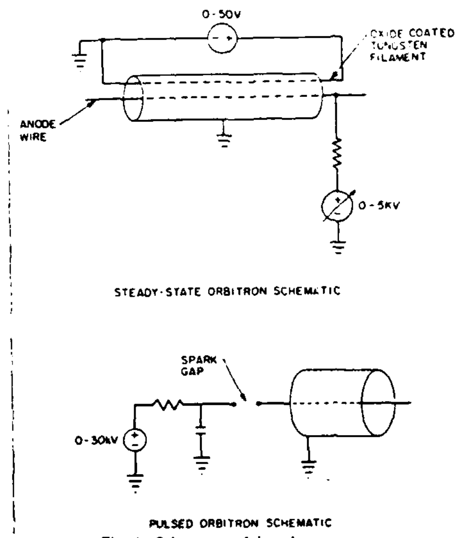

Fig. 1. Schematics of the orbitron maser.

The first method utilizing an axial microwave beam is shown in Fig. 2. This microwave beam is then used to determine the average number density in the device by finding the lowest frequency beam that will pass through the device without being cut off. Because of the waveguide-like characteristics of a plasma, we can assume that the frequency we observe is at or slightly higher than the electron plasma frequency and so

$$\Omega_b \sim \Omega_{pe} = 8.98(N_e)^{0.5}\ [\mathrm{Hz}] \qquad (1)$$

where N_e is the background electron number density in MKS units, Ω_b is the beam frequency, and Ω_{pe} is the electron plasma frequency [3]. This allows us to get the maximum in time of the average number density across the plasma contained illuminated by the microwave beam. We also monitored the maximum in time of the microwave frequency self-emitted by the orbitron maser while the microwave beam was passed down the device. This allows us to compare the plasma frequency to the emitted frequency to see if there is any interrelation between these

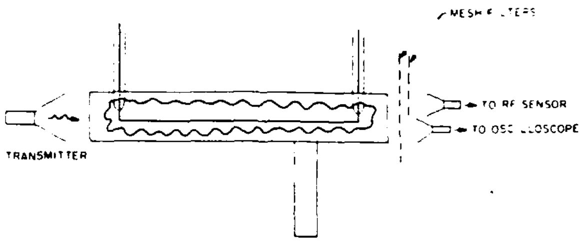

Fig. 2. Beam-probing experiment

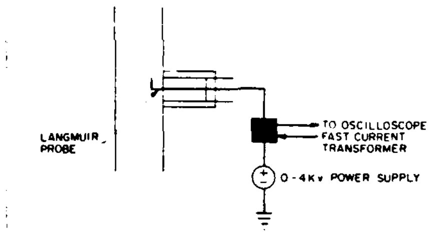

Fig. 3. Schematic of the sensing circuit.

two. The power emitted by the probing beam was approximately 1 mW.

The second method of experimentation utilized a radially inserted Langmuir probe to make profile measurements across the plasma radius, near the central wire. This approach utilized the classic methodology developed by Langmuir [4] with a unique feature; i.e., since the plasma is pulsed, it makes it very hard to take a complete probe curve during any one pulse. Therefore, we took the maximum in time of the current observed during several plasma pulses, and then changed the probe voltage after each data point to provide the Langmuir probe voltage sweep.

The current sensing was accomplished by the circuit shown in Fig. 3. It utilized a special current transformer which has a 2-ns rise time, and allowed us to monitor very fast changes in the plasma.

In the experiment to determine the effects of magnetic field on the device, we placed the device either perpendicular or parallel to the poles of an electromagnet. The field was then varied and measured using a calibrated Hall probe. We measured the RF output of the device simultaneously using a X-band horn an a crystal detector.

III. Experimental Results

We performed several experiments using the microwave beam probing procedure, as shown in Fig. 2. Fig. 4 is a characteristic example of the results we get. In this particular example, the voltage on the central wire was 6 kV with a background pressure of 20 μm.

We started probing the tube with a beam frequency of 28 GHz and found that the frequency was cut off, as shown in Fig. 4(a). The frequency was then raised until the beam

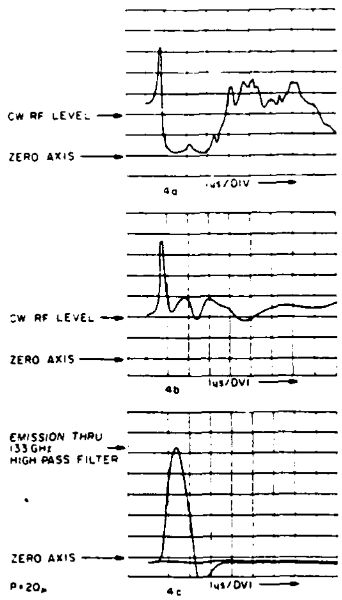

Fig. 4. Typical results of beam-probing experiment.

showed no signs of cut off. The uninterrupted signal occurred at 36 GHz, as shown in Fig. 4(b). This corresponds to an electron number density of 1.44×10^{20} electrons/m^3 using (1). We also observed the frequency emission during the probing of this device using an indium antimodide crystal as a detector with a set of special high-pass filters and supplementary mesh filters to determine the band of output. There will be more information presented on this subject later in this paper. The waveshape is a consequence of the detector response time. This method demonstrated that the frequency of output was at least 133 GHz, as shown in Fig. 4(c). This gives a minimum emitted Ω_r to electron plasma frequency Ω_{pe} ratio of 3.69 with a maximum error of +35 percent. We have also observed ratios of 5 to 1 or greater and ratios of less than 3.5 [2].

If one notes that the peak plasma density occurs later in time than the microwave emission, one finds the Ω_r/Ω_{pe}

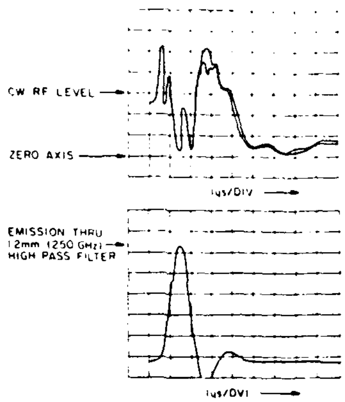

Fig. 5. 37.5-GHz probe. The 37.5-GHz probing signal is not cut off at the time of 1.2-mm pulsed emission.

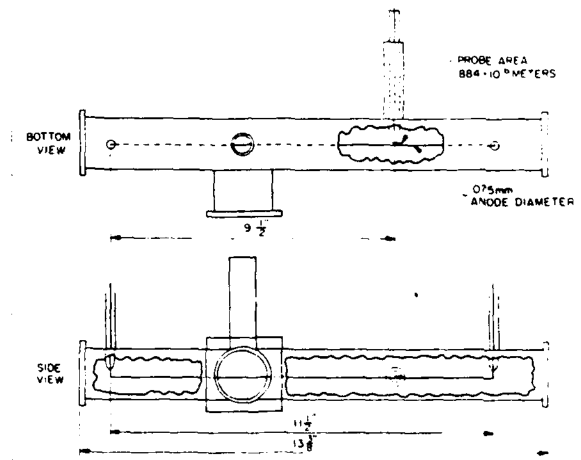

Fig. 6. Langmuir probe device.

ratios get even higher, as shown in Fig. 5. In this particular instance, the microwave burst starts about three quarters of a microsecond before the microwave beam is cut off. This gives a Ω_c/Ω_{pe} ratio of 6.7. The data that we have gathered in this experiment show no evidence that there is a constant ratio between Ω_c and Ω_{pe}. From this we conclude that there is no simple linear dependence between the frequency emitted by the maser and the electron plasma frequency, as claimed by others [5], [6].

For performing point measurements in our experiment, a Langmuir probe was inserted into a orbitron maser, as shown in Fig. 6. We took data at three points. These points were radially displaced from the centerline of the orbitron maser by 1, 2, and 3 mm, and the probe had an area of 0.884×10^{-6} m^2. While the data were taken, we also monitored the peak frequency emitted by the maser, to allow us to obtain Ω_c/Ω_{pe} ratios. The data that were taken are given in Table I, except for the second and third data runs at the 3-mm point. These missing data runs are characteristic of the ones given in this paper. These data are plotted in Fig. 7. In all of these experiments, the ion current that was observed was insignificant.

The plots shown in Fig. 7 were reduced using the classical Langmuir methods. The data yielded number densities ranging from about 1.5×10^{18} electrons/m^3 to 6×10^{17} electrons/m^3, as plotted in Fig. 8. These data give a remarkably straight line indicating an exponential decay of the electron density as one travels outward in radius. This gives us a good indication that we are in the presence of a logarithmic potential well. We observed a peak fre-

TABLE I

LANGMUIR PROBE DATA

1 mm Displacement		2 mm Displacement			3 mm Displacement		
			Current (ma)			Current (ma)	
Voltage	Current (ma)	Voltage	Set 1	Set 2	Voltage	Set 1	Set 4
40	-	40	[illegible]	[illegible]	[illegible]	-	[illegible]
50	3	50	16	16	41	-	2
60	4	60	25	27.5	45		4
70	8	70	35	50	47		6
80	15	80	60	[illegible]	50	10	8
90	30	90	80	[illegible]	52	-	10
100	40	100	120	120	55		12
110	60	110	140	140	57		16
120	70	120	160	160	60	25	18
130	100	130	180	[illegible]	61		25
140	150	140	-	200	70	40	30
150	200	150	-	220	72	-	35
170	250				74		40
190	300				76	-	45
					80	50	50
					85	-	60
					90	60	70
					95	-	80
					100	80	90
					110	110	-
					120	120	-
					130	140	-

quency output of 38 GHz ±5 percent. This gives a Ω_e/Ω_{pe} ratio of 3.46. We also computed the electron kinetic temperature from the data in Table I. These data are plotted in Fig. 9. These data show strong evidence of electron heating near the central anode. This indicates the presence of strong radial electric fields in the device. The Debye length was about one third of the probe radius.

To perform the frequency diagnostics, a set of special high-pass filters were used. These special filters have a transition from cut off to pass of 1 percent, or less, of the nominal value. Fig. 10 shows the typical response curve for one of these filters, with the curve for a mesn filter plotted as a comparison.

In determining the magnetic field effects we obtained interesting results, some of which are similar to those found in 1981 and 1984 [7]. In this experiment, it was found that the instability that drives the orbitron was damped with a suprisingly small transverse magnetic field. The transverse field needed to damp the instability totally, as shown in Fig. 11(a), was as small as 70 G. This very small damping field suggests that orbital motion is being perturbed and electrons are being lost from the system. The damping field was slightly dependent on the configuration of the device. In particular, it depended on the type of electron confinement that was used. The transverse field required to affect both confinement cases, shown in Fig. 11(a), is much lower that the 3000-G limit stated by Schumacher and Harvey [5]. Fig. 11(b) shows the similar effect of an axial magnetic field on the output of the device. The damping field in the axial case was also 70 G. This is similar to results obtained in 1981 and 1984 with a much larger diameter cavity [7].

IV. CONCLUSION

In order to better understand how our orbitron maser operates, we have been performing a series of diagnostic experiments to find out the conditions inside the device. These experiments include probing with microwave radiation to determine the electron plasma frequency, and the use of Langmuir probes to get radial electron temperature and number density measurements. We also observed the highest frequency emitted by the device at the time of the measurements.

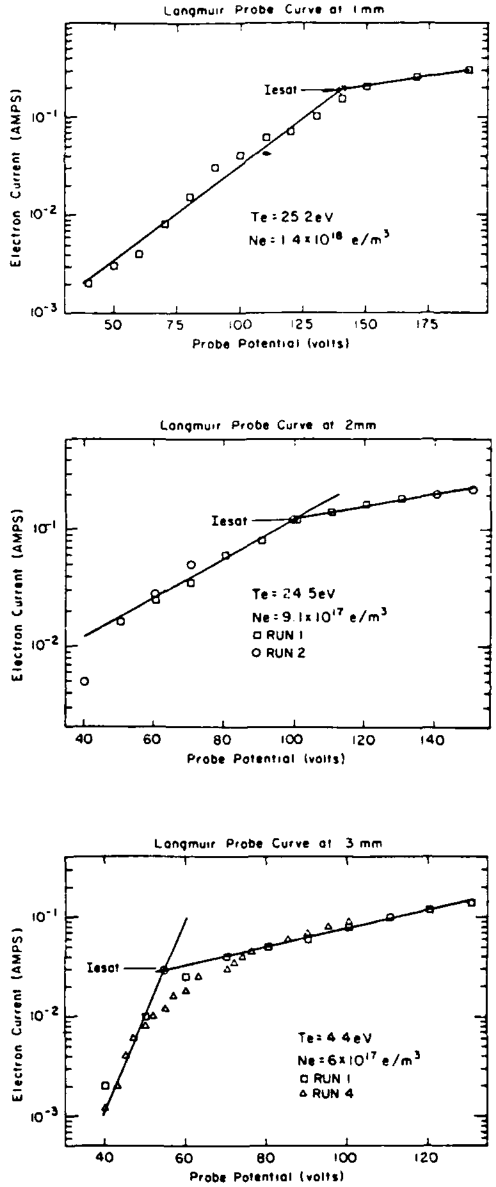

Fig. 7. Langmuir probe plots of electron current

After analyzing the data we found in the two experiments, we found that there was no direct evidence of a

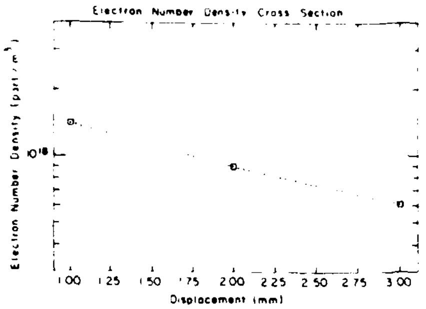

Fig. 8. Electron number density cross section.

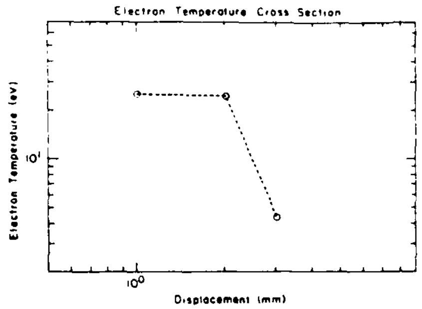

Fig. 9. Electron temperature cross section.

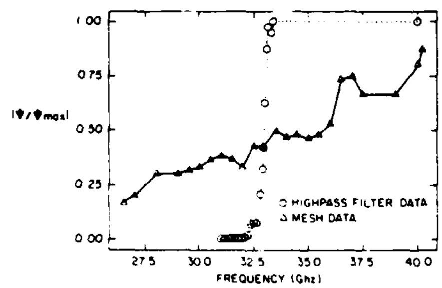

Fig. 10. Special filter response.

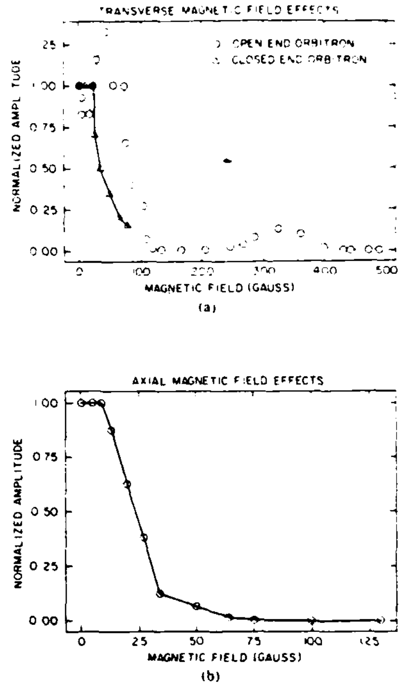

Fig. 11. (a), (b) Magnetic field effects.

simple linear relationship between the number density and the frequency of output. This is apparently due to the fact that there is no relation between the frequency of output and electron plasma frequency. We also found that the number density, close to the wire, is related exponentially to the distance from the central axis, and the electron kinetic temperature increases dramatically as one gets closer to the central axis. These two facts indicate to us that there is indeed a strong logarithmic potential well near the central wire, as we had previously surmised [1]. In addition, we found that the electrons are very hot near the central wire, while the ions in the region are very cold.

We have also experimentally repeated earlier studies of the effects of transverse and axial magnetic field on the device. In this experiment, we found that only a small magnetic field is required to damp the instability. This field is on the order of 70 G, not 3000 G, as claimed by others [5], which suggests that orbital motion is being perturbed and electrons are being lost from the system. This critical field is slightly dependent on end confinement of the electrons.

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Time dependent upward frequency shifts in the Orbitron MASER

MARK RADER†, FRED DYER†, and IGOR ALEXEFF†

In our experiments with the pulsed Oribtron MASER, we have noted that there is an upward chirp in frequency even though the anode voltage is decreasing. We have found theoretically that this is a natural consequence of the negative-mass instability and the chirp rate can be predicted from this theory. Experimental data we have obtained is also in good agreement with these predictions.

1. Introduction

In experiments with the Orbitron Maser (Alexeff *et al.* 1980, 1984, 1985), it has been noted by ourselves and others (Alexeff *et al.* 1987, Schumacher and Harvey 1984) that the frequency shifts upward rapidly in time. In an effort to better understand this upward shift in frequency, we have been studying the driving mechanism which produces the rf radiation. We have found from this study that the shift upward in time is a natural consequence of the negative-mass instability which drives the Orbitron, and the electron feed mechanism.

The electrons, which drive the negative-mass instability, are born on the outer edge of the cavity-wire system and spiral inwards. Since the frequency output of the electrons is inversely proportional to the electron radius in the system, and the lower electron orbits are empty at the beginning of each pulse, one would expect to see a shift upward on frequency as the pulse progresses even though the potential well is collapsing (Schumacher and Harvey 1984). Using this concept, we are able to predict, from theory, the rate at which the frequency chirps upwards. These predictions agree quantatively with what we have observed experimentally.

2. Theory

The Orbitron MASER is a device in which electrons orbit a positively charged wire placed inside a circular cavity resonator. The rotating electrons couple to microwave cavity modes and generate rf radiation. The basic formula for the frequency of this radiation emitted by monoenergetic circular orbits is given by

$$v = \frac{1}{2\pi r}\left(\frac{zeV}{m_e \ln(r_2/r_1)}\right)^{1/2} \tag{1}$$

where v is the frequency emitted, r is the radius of the electrons orbit, ze is the sign and charge of the electrons, V is the difference in potential between the inner-wire and the outer cavity, m_e is the electron mass, and r_2/r_1 is the ratio of the cavity radius to the wire radius (Schumacher and Harvey 1984). MKS units are used exclusively.

It can be seen from eqn. (1) that lowering the applied voltage reduces the output frequency, while the movement of the electrons from a larger to a smaller radius (a

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† Electrical Engineering Department, University of Tennessee, Knoxville, TN 37996-2100, USA.

natural consequence of the negative-mass instability) raises it, but the effect of the voltage reduction is much smaller than the decrease in the orbital radius. To study the effect quantatively, one must differentiate eqn. (1) as shown below,

$$\frac{dv}{dt} = -\frac{1}{2\pi r^2}\left(\frac{zeV}{m_e \ln\left(\frac{r_2}{r_1}\right)}\right)^{1/2}\frac{dr}{dt} + \frac{1}{2\pi r}\left(\frac{zeV}{m_e \ln(r_2/r_1)}\right)^{1/2}(1/2V)\frac{dV}{dt} \tag{2}$$

This equation can be simplified considerably by writing it in terms of the unshifted frequency output,

$$\frac{dv}{dt} = -\frac{v}{r}\frac{dr}{dt} + \frac{v}{2}\frac{1}{V}\frac{dV}{dt} \tag{3}$$

For the above equation, one already knows v, r, V and dV/dt. Only the value of dr/dt needs to be computed.

To compute dr/dt, one has an additional experimental piece of data, the emitted rf power (W). This power must be equal to the product of the total contained charge (Q), the local electric field (E), and the rate of motion of the charge through that field (dr/dt). Mathematically, we have

$$W = -QE dr/dt \tag{4}$$

As a first estimate for Q, we use the maximum amount of charge capable of being confined electrostatically at radius r without violently perturbing the system,

$$Q = 2\pi r l \epsilon_0 E, \tag{5}$$

here, l is the length of the circular system, and ϵ_0 is the permittivity of free space. Thus one finds the following expression,

$$\frac{dr}{dt} = -W(2\pi l \epsilon_0 r E^2)^{-1} \tag{6}$$

Substituting this into eqn. (3) along with the equation for an electric field in a circular system, one gets

$$\frac{dv}{dt} = \frac{vW\left(\ln\left(\frac{r_2}{r_1}\right)\right)^2}{2\pi l \epsilon_0 V^2} + \frac{v}{2}\frac{1}{V}\frac{dV}{dt} \tag{7}$$

where dV/dt is a negative quantity.

We can now evaluate the above expression, using characteristic data tabulated below:

$$v = 3 \times 10^{10}\ \text{(Hz)}$$

$$W = 10\ \text{watts}$$

$$V = 4\,\text{kV}_{\text{peak}}$$

$$r_2/r_1 = 333{\cdot}3$$

$$dV/dt = -4 \times 10^9\ \text{v/sec}$$

$$l = 0{\cdot}07\ \text{metres}$$

This data gives us that,

$$d\nu/dt = 1{\cdot}6 \times 10^{17} - 1{\cdot}5 \times 10^{16} = 1{\cdot}45 \times 10^{17}\,\mathrm{Hz}$$

So one finds that the frequency growth rate due to the instability is ten times that of the frequency decay rate due to the decline in voltage. In our experiments we have found that $d\nu/dt$ was approximately $5{\cdot}5 \times 10^{17}$ Hz/s which is in good agreement with the predicted value. One notes that the largest possible contained charge (Q) was used. Using smaller values of Q only causes the frequency to chirp up faster, so the largest value seems appropriate. A similar treatment can be used for the elliptical orbits predicted by (Burke *et al.* 1986).

3. Conclusion

In our experiments with the Orbitron MASER, it has been noted by ourselves and others that the output frequency chirps upward even though the anode voltage is decreasing. We have measured this chirp rate to be about $5{\cdot}5 \times 10^{17}$ Hz/s. We have also predicted what the minimum chirp rate should be, from the negative-mass instability that produces the rf radiation. This rate is $3{\cdot}5 \times 10^{17}$ Hz/s and is in good agreement with what we observe. These facts lead us to conclude that this theory is indeed coupled to the driving mechanism behind the Orbitrons frequency output and that this is the reason for the shift upward in time in our pulsed Orbitron MASER.

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Time Dependent Upward Frequency Shifts in the Orbitron MASER*

by

Mark Rader, Fred Dyer, and Igor Alexeff
Electrical Engineering Department
University of Tennessee
Knoxville, TN 37996-2100

Abstract

In our experiments with the pulsed Orbitron MASER, we have noted that there is an upward chirp in frequency even though the anode voltage is decreasing. We have found theoretically that this is a natural consequence of the negative-mass instability and the chirp rate can be predicted from this theory. Experimental data we have obtained is also in good agreement with these predictions.

Introduction

In experiments with the Orbitron Maser, it has been noted by ourselves and others[1,2] that the frequency shifts upward rapidly in time. In an effort to better understand this upward shift in frequency, we have been studying the driving mechanism which produces the R.F. radiation. We have found from this study that the shift upward in time is a natural consequence of the of the negative-mass instability which drives the Orbitron, and the electron feed mechanism.

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pulse, one would expect to see a shift upward on frequency as the pulse progresses even though the potential well is collapsing.[2] Using this concept, awe are able to predict, from theory, the rate at which the frequency chirps upward. These predictions agree quantatively with what we have observed experimentally.

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It can be seen from equation 1 that lowering the applied voltage reduces the output frequency, while the movement of the electrons from a larger to a smaller radius (a natural consequence of the negative-mass instability) raises it but the effect of the voltage reduction is much smaller than the decrease in the orbital radius. To study the effect quantatively, one must differentiate equation 1 as shown below,

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As a first estimate for Q, we use the maximum amount of charge capable of being confined electrostatically at radius r without violently perturbing the system,

$$Q = 2\pi r \ell \varepsilon_0 E \tag{5}$$

here, ℓ is the length of the circular system, and ε_0 is the permittivity of free space. Thus one finds the following expression

$$\frac{dr}{dt} = -W(2\pi \ell \varepsilon_0 E^2)^{-1} \tag{6}$$

Substituting this into equation 3 along with the equation for a electric field in a circular system, one gets

$$\frac{dv}{dt} = \frac{vW\left(\ell n\left(\frac{r_2}{r_1}\right)\right)^2}{2\pi \ell \varepsilon_0 V^2} + \frac{v}{2}\frac{1}{V}\frac{dV}{dt} \tag{7}$$

where dV/dt is a negative quantity.

We can now evaluate the above expression, using characteristic data tabulated below;

$w = 3 \times 10^{10}$ (Hz)

$W = 10$ watts

$V = 4\ kV_{peak}$

$r_2/r_1 = 333.3$

$dV/dt = -4 \times 10^9$ v/sec

$\ell = .07$ meters

This data gives us that,

$$dv/dt = 1.6 \times 10^{17} - 1.5 \times 10^{16} = 1.45 \times 10^{17} \text{ Hz/sec.}$$

So one finds that the frequency growth rate due to the instability is ten times that of the frequency decay rate due to the decline in voltage. In our experiments we have found that dv/dt was approximately 5.5×10^{17} Hz/sec, which is, in good agreement with the predicted value. One notes that the largest possible contained charge (Q) was used. Using smaller values of Q only causes the frequency to chirp up faster, so the largest value seems appropriate. A similar treatment can be used for the elliptical orbits predicted by Manheimer et al.[3]

Conclusion

In our experiments with the Orbitron MASER, it has been noted by ourselves and others that the output frequency chirps upward even though the anode voltage is decreasing. We have measured this chirp rate to be about 5.5×10^{17} Hz/sec. We have also predicted what the minimum chirp rate should be, from the negative-mass instability that produces the R.F. radiation. This rate is 3.5×10^{17} Hz/sec and is in good agreement with what we observe. These

facts lead us to conclude that this theory is indeed coupled to the driving mechanism behind the Orbitrons frequency output and that this is the reason for the shift upward in time in our pulsed Orbitron MASER.

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Stimulated Emission, Amplification, and Upward Frequency Shift of the Orbitron MASER.*

Igor Alexeff, Mark Rader, and Fred Dyer

Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

Introduction

The Orbitron Maser is a device in which R.F. radiation is produced by electrons in elongated or circular orbits around a positively charged central anode wire. This wire is surrounded by a circular cylinder which is at ground potential. This cylinder acts both as a cathode and as a cavity resonator. The frequency of this radiation, for circular orbits, (v) is,

$$v = \frac{1}{2\pi r}\left(\frac{Zev}{m_e \ln(r_2/r_1)}\right)^{1/2}, \tag{1}$$

where r is the radius of the electron, Ze is the sign and charge of the electron, V is the difference in potential between the inner wire and the outer cavity, m_e is the electron mass, and r_2/r_1 is the ratio of the cavity radius to the wire radius[1] MKS unit are used.

This device has two distinct modes of operation. In the first mode of operation, the gain of the device is very large so that the device is triggered into self oscillation by thermal noise. We have detected radiation at a frequency of 1 THz being emitted by this type of maser.[2]

In this mode of operation, it has been seen by ourselves and others[3,4] the frequency chirps upward. This occurs even though the anode voltage is decreasing. We have found that it is possible to predict the rate of chirp theoretically and our predictions are in good agreement with experimental results.

The second mode of operation is a low gain mode. In this mode, emission from this device is stimulated by an externally applied signal of the frequency one wishes emitted.

Theory of the Upward Frequency Chirp

From examining the basic Orbitron theory we have found that the shift upward in frequency with time is a natural consequence of the negative-mass instability which drives the Orbitron, and the electron feed mechanism.

The electrons, which drive the negative-mass instability, are born on the outer edge of the cavity-wire system and spiral inwards. Since the frequency output of the electrons is inversely proportional to the electrons' radius in the system, and the lower electron orbits are depleted at the beginning of each pulse, one would expect to see a shift upward in frequency as the pulse progresses even though the potential well is collapsing.[3]

From equation 1 we can see that lowering the applied voltage reduces the output frequency, while the movement of the electrons from a larger to a smaller radius (a natural consequence of the negative-mass instability) raises it, but the effect of the voltage reduction is much smaller than the decrease in the orbital radius. This is because the frequency is dependent only on $V^{1/2}$ and it is inversely proportional to the radius. To study the effect quantatively, one must differentiate equation 1 as shown below,

$$\frac{dv}{dt} = -\frac{1}{2\pi r^2}\left(\frac{ZeV}{m_e \ln\left(\frac{r_2}{r_1}\right)}\right)^{1/2}\frac{dr}{dt} + \frac{1}{2\pi r}\left(\frac{ZeV}{m_e \ln(r_2/r_1)}\right)^{1/2}\frac{1}{2v}\frac{dV}{dt} \tag{2}$$

This equation can be simplified considerably by writing it in terms of the unshifted frequency output,

$$\frac{dv}{dt} = -\frac{v}{r}\frac{dr}{dt} + \frac{v}{2V}\frac{dV}{dt} \tag{3}$$

For the above equation, one already knows v, r, V and dV/dt. Only the value of dr/dt needs to be computed.

To compute dr/dt, one has an additional piece of data, the total emitted R.F. power (W). This emitted power must be equal to the product of the total contained charge (Q), the local electric field (E), and the rate of motion of the charge through that field (dr/dt). Mathematically, we have

$$W = -QE\,dr/dt \tag{4}$$

One can estimate what the contained charge Q is by using the total charge that can be contained in the orbitron without violently perturbing the system. This will give the lowest chirp rate that the device can have. If one inserts this term into equation 4, and solves for dr/dt one gets,

$$\frac{dr}{dt} = -w(2\pi \ell \epsilon_0 E^2)^{-1} \tag{5}$$

where, ℓ is the length of the circular system and ϵ_0 is the permittivity of free space. Substituting this into equation 3 along with the equation for an electric field in a circular system, one gets,

$$\frac{dv}{dt} = \frac{vW\left(\ln\left(\frac{r_2}{r_1}\right)\right)^2}{2\pi \ell \epsilon_0 V^2} + \frac{v}{2}\frac{1}{V}\frac{dV}{dt} \tag{6}$$

where dV/dt is a negative quantity.

We can now evaluate the above expression, using characteristic data tabulated below;

$v = 3 \times 10^{10}$ (Hz),
W = 10 watts,
V = 4 kV_{peak},
$r_2/r_1 = 333.3$,
$dV/dt = -4 \times 10^9$ V/sec,
$\ell = .07$ meters,

This data gives us that,

$$dv/dt = 1.6 \times 10^{17} - 1.5 \times 10^{16} = 1.45 \times 10^{17} \text{ Hz/sec.}$$

So one finds tha the frequency growth rate due to the instability is ten times that of the frequency decay rate due to the decline in voltage. In our experiments we have found that dv/dt was approximately 5.5×10^{17} Hz/sec. This indicates that the actual charge contained in the system is smaller than estimated. As an estimate of the total power emitted, we used total power that was in the band of interest and did not include any emission in lower frequency bands. This would also lower the computed chirp rate below the observed chirp rate.

Experimental Results of Low Gain Operation

One of the concepts of any masing or lasing device is that it can be run in a mode where it can amplify an external signal. We have acomplished this with the Orbitron Maser. In two separate devices, one a beer can placed in a bell jar and the other using a sealed piece of pipe approximately 1.75 meters long and 7.5 cm in diameter, we have seen strong evidence of externally stimulated emission, as shown in Figure 1.

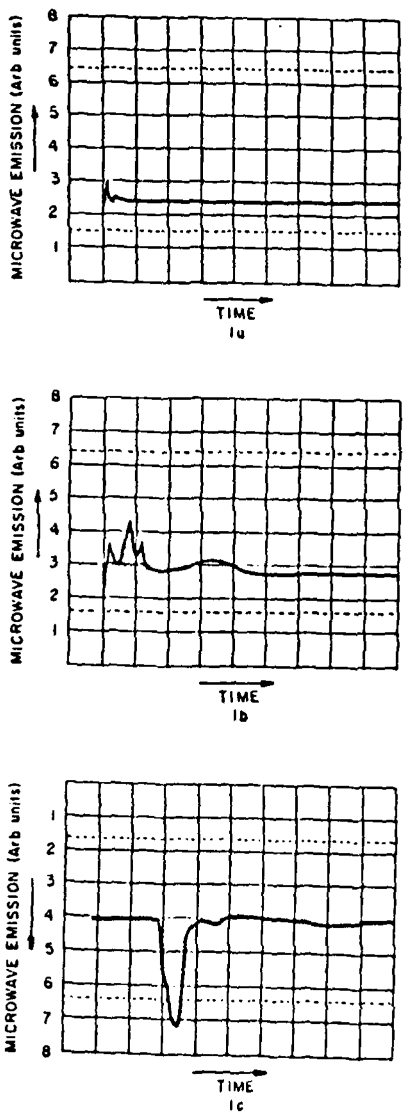

Figure 1

In Figure 1a, we are pulsing our beer can maser with no stimulating signal and observe no output signal from a horn-crystal detector set up. If a continuous external pump signal is fed into the device, as is done in Figure 1b, it can be seen that microwave emission occurs and we found that this signal has more power than the pump signal. Figure 1c is the same type of situation as Figure 1b except that we are using the 1.75 meter pipe instead of the beer can.

To reach this mode of operation we first looked at the spectral output of the device, then we lowered the wire voltage until there was no emission in the frequency range we were observing and above. Then an external signal of known amplitude was fed into the device, and amplification was observed.

Conclusion

The Orbitron Maser is a negative-mass unstable device, which can be used to produce microwave radiation. This device, in the pulsed mode, produces R.F. radiation up to a certain peak frequency. This peak frequency shifts upward in time and the rate of this shift is predictable from the basic Orbitron theory. This predicted rate of shift is in good agreement with experimental results. We have also been able by adjusting the operating conditions of the device to reach a state in which the emission of the device is controlled by an externally supplied pump signal.

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Theory of first-order plasma heating by collisional magnetic pumping

M. Laroussi[a] and J. Reece Roth
Department of Electrical and Computer Engineering, The University of Tennessee, Knoxville, Tennessee 37996-2100

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Plasma heating by collisional magnetic pumping is investigated theoretically. This treatment yields solutions to the energy transfer equations in the form of an energy increase rate, which gives quantitatively the amount of energy increase per rf driving cycle. The energy increase rates (or heating rates) proportional to the first and second powers of the field modulation factor δ (defined as the ratio of the change in the magnitude of the magnetic field to its background dc value) are derived for an arbitrary rf waveform of the pumping magnetic field. Special cases are examined, including the sinusoidal and sawtooth pumping waveforms. The energy increase rate in the case of a sawtooth waveform was found to be proportional to the first power of δ (first-order heating). This heating rate is many orders of magnitude larger than heating for the sinusoidal case: The latter is proportional to the square of δ and is strongly dependent on the collisionality of the plasma. The use of a sawtooth pumping waveform improves the efficiency of collisional magnetic pumping and heating rates comparable to those possible with ion or electron cyclotron resonance heating methods may be achieved.

I. INTRODUCTION

Collisional magnetic pumping[1-6] is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field $B = B_0[1 + \delta f(t)]$, where B_0 is the uniform steady-state background magnetic field, δ is the field modulation factor defined as $\delta = \Delta B / B_0$, and $f(t)$ is a periodic function of time. Figure 1 illustrates such a situation. The origins of collisional magnetic pumping date to the beginnings of fusion research in 1953,[1] when Spitzer and Witten proposed to heat a plasma with a sinusoidally perturbed magnetic field. The theory of collisional magnetic pumping with a sinusoidal magnetic perturbation was first published in the unclassified literature by Schluter in 1957.[2] Early theoretical research by Berger and others at the Princeton Plasma Physics Laboratory, following the work of Spitzer and Witten,[1] was summarized by Berger *et al.*[3] These authors, in agreement with Schluter,[2] quoted a heating rate proportional to the square of the magnetic field perturbation, which was also a strong function of the collision frequency of the plasma. The work of Berger *et al.*[3] appeared in subsequent texts[4-6] without embellishment. No further work on collisional magnetic pumping appears to have been done until recently,[7-9] possibly because the low heating rates resulting from a sinusoidal magnetic perturbation were of second order and orders of magnitude smaller than that of competitive heating methods such as ion or electron cyclotron resonance heating.

Contrary to ohmic heating, where the electric field is parallel to the confining axial magnetic field, the oscillating electric field in collisional magnetic pumping is produced by variation of the axial magnetic field and thus is perpendicular to the field. This type of heating is called "magnetic pumping" as a result of the existence of a compressional wave propagating perpendicular to the background magnetic field and causing the plasma to be cyclically compressed and relaxed by an alternating $E \times B$ force. This is illustrated in Fig. 2. The compressive wave is a magnetosonic wave (or magnetoacoustic wave). The magnetosonic wave is an extraordinary electromagnetic mode with a frequency well below the gyrofrequency. Contrary to Alfvén waves, which travel along B_0, magnetosonic waves travel across B_0 at the Alfvén speed $V_A = B_0(1/\mu n_0 m_i)^{1/2}$, where n_0 is the charged particle density, m_i is the ion mass, and μ is the permeability of the plasma.

To achieve collisional heating the following inequalities have to be satisfied[3]:

$$\tau_{cy} \ll \tau_c \sim \tau_f \ll \tau_{tr},$$

where τ_{cy}, τ_c, τ_f, and τ_{tr} are, respectively, the gyration period, the collision time, the period of the oscillating field, and the transit time of the particles through the heating region. The particles suffer many collisions while crossing the heating region, but since the period of the oscillating field is much larger than the gyration period, the magnetic moment of the particles is a constant of motion between collisions. The magnetic field assumes the form $B = B_0[1 + \delta f(t)]$, where $\delta \ll 1$, so that the external oscillator provides a small perturbation on the original static magnetic field. If the heating region is of length L and the parallel velocity of the particles is $v_\parallel$, the above inequalities can also be written as

$$v_\parallel / L \ll v_c \sim \omega \ll \omega_{cy},$$

where v_c, ω, and ω_{cy} are, respectively, the collision frequency, the driving frequency, and the gyrofrequency.

II. THEORETICAL ANALYSIS

In the absence of collisions, the constancy of the magnetic moment makes it possible to obtain a relationship

[a] Present address: Department of Electrical Engineering, Technical University, Sfax, Tunisia.

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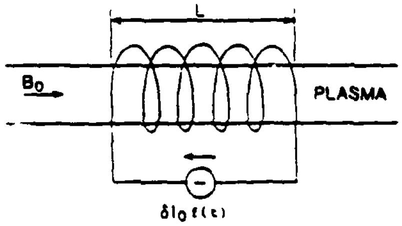

FIG. 1. Exciter coil around a cylindrical plasma.

between the time rate of change of the perpendicular component of the energy and the time rate of change of the magnetic field. Thus by taking the derivative of the magnetic moment $\mu = E_\perp/B$ with respect to time we obtain

$$\frac{d\mu}{dt} = 0 = \frac{1}{B}\frac{dE_\perp}{dt} - \frac{E_\perp}{B^2}\frac{dB}{dt}, \tag{1}$$

from which we obtain

$$\frac{dE_\perp}{dt} = \frac{E_\perp}{B}\frac{dB}{dt}. \tag{2}$$

The total energy E of the ions is given by

$$E = E_\parallel + E_\perp, \tag{3}$$

where $E_\parallel$ is the ion energy along the magnetic field lines and $E_\perp$ is the ion energy perpendicular to the magnetic field lines, with two degrees of freedom.

If no collisions occur, the perpendicular component of the ion energy $E_\perp$ oscillates with the frequency ω and no net heating occurs. However, if collisions do occur, some of the energy in the perpendicular component is transferred to the parallel component $E_\parallel$. In kinetic equilibrium, the parallel component of the energy will be equal to one-half the perpendicular component as a result of equipartition. When the perpendicular component is driven by magnetic pumping, a periodic departure from equipartition occurs and energy can be transferred between the parallel and perpendicular components. This may be expressed mathematically by adding a collisional term to Eq. (2)[4]:

$$\frac{dE_\perp}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} - \nu_c\left(\frac{E_\perp}{2} - E_\parallel\right), \tag{4}$$

$$\frac{dE_\parallel}{dt} = \nu_c\left(\frac{E_\perp}{2} - E_\parallel\right). \tag{5}$$

Now summing Eqs. (4) and (5) and using Eq. (3) one obtains

$$\frac{dE}{dt} = \frac{E_\perp}{B}\frac{dB}{dt} = \mu\frac{dB}{dt}. \tag{6}$$

Thus the rate of change of the total ion energy is proportional to the magnetic moment and the time rate of change of the magnetic field.

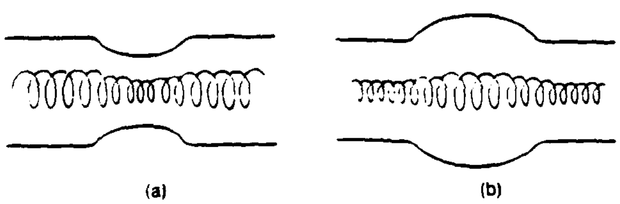

FIG. 2. Particle orbits in a sinusoidally perturbed magnetic field. (a) Plasma compressed during the positive half-cycle, (b) plasma relaxed during the negative half-cycle.

The net energy transfer can be obtained by taking the second derivative of Eqs. (6) and then using Eqs. (4) and (5) to eliminate the first derivative of the parallel and perpendicular components of the energy. Further, using Eq. (6) to eliminate the perpendicular component of energy one obtains

$$\frac{d^2E}{dt^2} - \left[-\frac{3}{2}\nu_c + \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right]\frac{dE}{dt} - \frac{\nu_c}{B}\frac{dB}{dt}E = 0. \tag{7}$$

Substituting the expression $B = B_0[1 + \delta f(t)]$ for B into Eq. (7) yields

$$\frac{d^2E}{dt^2} + \left(\frac{3}{2}\nu_c - \frac{f''(t)}{f'(t)}\right)\frac{dE}{dt} - \nu_c\frac{\delta f'(t)}{1+\delta f(t)}E = 0. \tag{8}$$

Let

$$A(t) = \tfrac{3}{2}\nu_c - f''(t)/f'(t), \tag{9}$$

$$g(t) = -\nu_c\{f'(t)/[1+\delta f(t)]\}. \tag{10}$$

Equation (8) can be written as

$$\frac{d^2E}{dt^2} + A(t)\frac{dE}{dt} + \delta g(t)E = 0. \tag{11}$$

Equation (11) is a homogeneous linear differential equation of second order with periodic coefficients; it describes the change in the total energy of the particles due to collisional magnetic pumping. Examples of such equations are the Mathieu and Hill equations which appear in astronomical and other applications, where the stability and perturbation of periodic systems are at issue. The general solutions of these equations have been given by Floquet.[10] Floquet's theory predicts a solution of the following form:

$$E(t) = a_1e^{\lambda_1 t}P_1(t) + a_2e^{\lambda_2 t}P_2(t). \tag{12}$$

The parameters λ_1 and λ_2 are called the characteristic exponents and can be calculated from the characteristic equation associated with the differential equation; $P_1(t)$ and $P_2(t)$ are periodic functions with a period equal to that of the coefficients of the differential equation. Since $\delta = \Delta B/B_0$ is a small quantity, Eq. (11) can be solved using a perturbation treatment around the parameter δ. The characteristic exponents λ_1 and λ_2 can be represented by the series[7,8]

$$\lambda_1 = -\tfrac{3}{2}\nu_c + \delta l_1 + \delta^2 l_2 + \cdots, \tag{13}$$

$$\lambda_2 = \delta l_1 + \delta^2 l_2 + \dots. \tag{14}$$

The solution associated with λ_1 is damped in time since the first term dominates the series and therefore does not represent steady-state heating. For this reason, only the solution associated with λ_2, with positive coefficients l_k, will be retained and used. The solution representing heating is then expressed as

$$E(t) = e^{\lambda_2 t}P_2(t). \tag{15}$$

Now $P_2(t)$ can be expanded as a series of the powers of δ as

$$P_2(t) = P_{20} + \delta P_{21}(t) + \delta^2 P_{22}(t) + \cdots, \tag{16}$$

where $P_{2i}(t)$ are periodic functions. The initial value is P_{20} and is set equal to 1 for the sake of simplicity. Now, by using the solution predicted by Floquet's theory[10] along with the above perturbation treatment, Eq. (11) can be solved for the different powers of the parameter δ.

E-58

Solving for the first power of δ, $g(t)$ can be expressed as

$$g(t) = -\nu_c f'(t), \tag{17}$$

$$E(t) = l_1 t + P_{21}(t). \tag{18}$$

Equation (11) is then reduced to

$$\frac{d^2 P_{21}(t)}{dt^2} + A(t)\frac{dP_{21}(t)}{dt} = K(t), \tag{19}$$

where

$$K(t) = -g(t) - l_1 A(t). \tag{20}$$

The homogeneous solution associated with Eq. (19) can be obtained by multiplying by the integrating factor[9]

$$\exp\left(\int_0^t A(u)du\right).$$

The homogeneous equation can then be written as

$$\frac{d}{dt}\left[\exp\left(\int_0^t A(u)du\right)\frac{dP_{21}}{dt}\right] = 0, \tag{21}$$

which leads to the solution

$$P_{21}(t) = C_1 + C_2\int_0^t e^{-a(s)}\,ds, \tag{22}$$

where

$$a(t) = \int_0^t A(u)du. \tag{23}$$

The general solution of Eq. (19) is calculated as follows. Multiplying Eq. (19) by the integrating factor $e^{a(t)}$ and integrating once, we find the expression

$$P'_{21}(t) = C_2 e^{-a(t)} + e^{-a(t)}\int_0^t K(s)e^{-a(s)}\,ds. \tag{24}$$

Integrating (24) gives

$$P_{21}(t) = C_1 + C_2\int_0^t e^{-a(s)}ds + \int_0^t e^{-a(s)}\left(\int_0^s K(u)e^{a(u)}\right)ds. \tag{25}$$

The second integral in Eq. (25) is integrated by parts and is

$$\int_0^t e^{-a(s)}\left(\int_0^s K(u)e^{a(u)}\right)ds = \left(\int_0^t e^{-a(u)}du\right)\left(\int_0^t K(u)e^{a(u)}du\right) - \int_0^t\left(\int_0^s e^{-a(u)}du\right)K(s)e^{a(s)}\,ds. \tag{26}$$

Equation (25) becomes

$$P_{21}(t) = C_1 + C_2\int_0^t e^{-a(s)}\,ds + \left(\int_0^t e^{-a(u)}du\right)\times\left(\int_0^t e^{a(u)}K(u)du\right) - \int_0^t e^{a(s)}\left(\int_0^s e^{-a(u)}du\right)K(s)ds. \tag{27}$$

The fact that $P_{21}(t)$ is a periodic function gives the conditions

$$P_{21}(T) - P_{21}(0) = 0, \quad P'_{21}(T) - P'_{21}(0) = 0. \tag{28}$$

Substituting (27) in conditions (28) leads to

$$C_2\int_0^T e^{-a(u)}du + \left(\int_0^T e^{-a(u)}du\right)\left(\int_0^T K(u)e^{a(u)}du\right) - \int_0^T\left(e^{a(s)}\int_0^s e^{-a(u)}du\right)K(s)ds = 0, \tag{29}$$

$$C_2(e^{-a(T)} - e^{-a(0)}) + e^{-a(T)}\int_0^T K(s)e^{a(s)}\,ds = 0. \tag{30}$$

Note that $e^{-a(0)} = 1$. Equation (30) gives

$$C_2 = \frac{e^{-a(T)}}{1 - e^{-a(T)}}\int_0^T K(s)e^{a(s)}\,ds. \tag{31}$$

Substituting (31) into (29) and letting

$$Q(s) = e^{a(s)}\left(\frac{1}{1 - e^{-a(T)}}\int_0^T e^{-a(u)}\,du - \int_0^s e^{-a(u)}\,du\right) \tag{32}$$

leads to the condition

$$\int_0^T K(s)Q(s)ds = 0. \tag{33}$$

Substituting $K(t) = -g(t) - l_1 A(t)$ into Eq. (33) gives

$$l_1 = -\frac{\int_0^T g(s)Q(s)ds}{\int_0^T A(s)Q(s)ds}. \tag{34}$$

Substituting $A(t)$ from Eq. (9) and $Q(s)$ from Eq. (32) into the denominator and integrating by parts gives

$$\int_0^T A(s)Q(s)ds = T,$$

so that

$$l_1 = -\frac{1}{T}\int_0^T g(s)Q(s)ds. \tag{35}$$

Knowing that

$$g(t) = -\nu_c f'(t),$$

$$A(t) = \tfrac{3}{2}\nu_c - f''(t)/f'(t),$$

and

$$a(t) = \tfrac{3}{2}\nu_c t - \ln(f'(t)/f'(0)),$$

the final expression for l_1 is

$$l_1 = \frac{\nu_c}{T}\int_0^T \exp\left(\frac{3}{2}\nu_c s\right)\left[\frac{1}{1 - \exp(-\frac{3}{2}\nu_c T)}\times\int_0^T \exp\left(-\frac{3}{2}\nu_c u\right)f'(u)du - \int_0^s \exp\left(-\frac{3}{2}\nu_c u\right)f'(u)du\right]ds. \tag{36}$$

The term representing heating in Floquet's[10] solution, Eq. (15), is, after expanding $e^{\delta l_1 t}$,

$$E(t) = E_0 + \delta[l_1 t E_0 + P_{21}(t)] + \text{higher order terms}. \tag{37}$$

The energy increase in a period $T = 2\pi/\omega$ is

$$\Delta E = \delta l_1(2\pi/\omega)E_0, \tag{38}$$

where $P_{21}(T)$ and $P_{21}(0)$ cancel each other as a result of the periodicity of $P_{21}(t)$. Here E_0 is the initial value of the total particle energy. The energy increase rate is given by

$$\Delta E/T = \delta l_1 E_0. \tag{39}$$

III. SECOND-ORDER HEATING WITH A SINE WAVE PERTURBATION

Let us now assume, as previously,[1-3] that the background magnetic field has a sinusoidal perturbation superimposed on it according to the expression

$$B = B_0(1 + \delta \cos \omega t). \tag{40}$$

Substituting $f(t) = \cos \omega t$ in Eq. (36) for l_1, it is easily shown that $l_1 = 0$. In this case, the energy increase is proportional to a higher power of δ than the first. Another way of checking the result (40) and at the same time calculating the next coefficient l_2 in the expansion is to return to the initial differential equation (8) and substitute $\cos \omega t$ for $f(t)$. In doing this, Eq. (11) becomes

$$\frac{d^2E}{dt^2} - \left(-\frac{3}{2}\nu_c + \frac{\omega \cos \omega t}{\sin \omega t}\right)\frac{dE}{dt} + \frac{\delta \nu_c \sin \omega t}{1 + \delta \cos \omega t} E = 0. \tag{41}$$

Since $\delta \ll 1$, the term $(1 + \delta \cos \omega t)^{-1}$ can be expanded in a Taylor series:

$$(1 + \delta \cos \omega t)^{-1} \simeq 1 - \delta \cos \omega t + \text{higher order terms}. \tag{42}$$

Substituting Eq. (42) into Eq. (41) one obtains

$$\frac{d^2E}{dt^2} - \left(-\frac{3}{2}\nu_c + \frac{\omega \cos \omega t}{\sin \omega t}\right)\frac{dE}{dt} + \delta \nu_c \omega \sin \omega t (1 - \delta \cos \omega t) E = 0. \tag{43}$$

Using Eq. (15) for the part of Floquet's solution[10] that represents heating and solving for the first power of δ, Eq. (43) becomes

$$\frac{d^2P_{21}}{dt^2} + \left(\frac{3\nu_c}{2} - \omega \cot \omega t\right)\frac{dP_{21}}{dt} = -\frac{3}{2} l_1 \nu_c + l_1 \omega \cot \omega t - \nu_c \omega \sin \omega t, \tag{44}$$

where P_{20} is set equal to 1 for the sake of simplicity.

The homogeneous solution of Eq. (44) is

$$P_{21}(t) = C_1 e^{(3\nu_c/2)t}\{a \cos \omega t + b \sin \omega t\} + C_2, \tag{45}$$

where

$$a = -\omega/(\omega^2 + \tfrac{9}{4}\nu_c^2), \tag{46}$$

$$b = -\tfrac{3}{2}\nu_c/(\omega^2 + \tfrac{9}{4}\nu_c^2). \tag{47}$$

The particular solution of Eq. (44) is

$$P_{21}(t) = -l_1 t + \nu_c a \sin \omega t - \nu_c b \cos \omega t + l_1 a \cot \omega t + (-l_1/\sin \omega t - \tfrac{3}{2}\omega)(a \cos \omega t + b \sin \omega t). \tag{48}$$

Now setting the secular term equal to zero [since $P_{21}(t)$ is periodic] one obtains the result $l_1 = 0$. This is in agreement with what was previously predicted. Solving for the second power of δ, Eq. (43) becomes

$$\frac{d^2P_{22}}{dt^2} + \left(\frac{3}{2}\nu_c - \omega \cot \omega t\right)\frac{dP_{22}}{dt} = -\tfrac{3}{2} l_2 \nu_c + l_2 \omega \cot \omega t + \nu_c \omega \sin \omega t \cos \omega t - \nu_c \omega \sin \omega t P_{21}(t). \tag{49}$$

As previously, the interesting part of the solution is the particular solution and the important part of the particular solution is the part containing the secular term P_{sec}. The latter is found to be

$$P_{sec} = (\tfrac{3}{2} l_2 \nu_c b + a l_2 \omega - \tfrac{1}{6}\nu_c \omega a)t. \tag{50}$$

Setting term (50) equal to zero and solving for l_2, we obtain

$$l_2 = \nu_c \omega^2/6(\omega^2 + \tfrac{9}{4}\nu_c^2). \tag{51}$$

To calculate the energy increase per cycle, the expression for the energy has to be expanded as

$$E(t) = e^{\delta^2 l_2 t} P_2(t) = (1 + \delta^2 l_2 t + \cdots)[P_{20} + \delta P_{21}(t) + \delta^2 P_{22}(t) + \cdots]. \tag{52}$$

Retaining only up to the second-order terms in δ, $E(t)$ can be expressed as

$$E(t) = P_{20} + \delta P_{21}(t) + \delta^2[P_{22}(t) + l_2 t P_{20}] + \text{higher order terms in } \delta. \tag{53}$$

At $t = 2\pi/\omega$, the energy has increased by

$$\Delta E = \delta^2 l_2 (2\pi/\omega) E_0. \tag{54}$$

Inserting the expression for l_2 in Eq. (54) gives

$$\Delta E = \delta^2 E_0(\pi/3)[\nu_c \omega/(\tfrac{9}{4}\nu_c^2 + \omega^2)] \text{joules/cycle}. \tag{55}$$

The energy increase rate is found by dividing ΔE by $\Delta t = 2\pi/\omega$ sec/cycle and taking the differential limit

$$\frac{dE}{dt} = \frac{\delta^2}{6}\frac{\omega^2 \nu_c}{\tfrac{9}{4}\nu_c^2 + \omega^2} E_0 \text{ Joules/sec}. \tag{56}$$

The result (56) agrees with the one found by Schluter[2] and Berger *et al.*[3] Equation (56) can be written as

$$\frac{dE}{dt} = \frac{E_0}{\tau_H} = \alpha E_0, \tag{57}$$

where τ_H is the heating time defined as

$$\tau_H \equiv 6[(\tfrac{9}{4}\nu_c^2 + \omega^2)/\delta^2 \omega^2 \nu_c] \tag{58}$$

and $\alpha \equiv 1/\tau_H$ is the heating rate coefficient. The optimum frequency at which the heating rate coefficient is maximum is

$$\omega_{opt} = \tfrac{3}{2}\nu_c \tag{59}$$

and the value of α at this frequency is

$$\alpha_{max} = \delta^2 \nu_c/12. \tag{60}$$

For a highly collisional plasma, $\nu_c \gg \omega$ and the heating rate can be approximated by

$$\frac{dE}{dt} \simeq \frac{2}{27}\frac{\delta^2 \omega^2}{\nu_c} E_0. \tag{61}$$

On the other hand, for a relatively collisionless plasma, $\nu_c \ll \omega$ and the heating rate can be expressed as

$$\frac{dE}{dt} \simeq \frac{\delta^2 \nu_c}{6} E_0. \tag{62}$$

As seen in the above analysis, the heating rate is proportional to ν_c in the low collisionality case and to ν_c^{-1} in the

highly collisional case. Figure 3 is a schematic plot of the heating rate coefficient α, the inverse of Eq. (58), versus the collision frequency. The fact that the collision magnetic pumping heating rate for a sinusoidal excitation has a maximum at $\nu_c = 2\omega/3$ can be used as a diagnostic for the effective collision frequency; the maximum energy coupling to the plasma occurs here and can be measured with standard rf techniques

To get a feeling for how different the rates of energy increase are in the above two cases, let us consider a plasma of fusion interest operating at the following parameters: $T_i = 2$ keV, $A = 2$, $n = 10^{19}/\text{m}^3$, $L = 0.5$ m, and $B_0 = 2.0$ T. The binary particle collision frequency in this case is $\nu_c = \upsilon_{ii} = 1/\tau_{ii} \approx 313$ Hz, leading to a heating rate coefficient

$$\alpha = \delta^2 \nu_c/6 = 52\,\delta^2/\text{sec}. \tag{63}$$

Now if anomalous resistivity is present in the plasma, the collision frequency due to turbulence, etc. can be on the order of 5 MHz,[11] leading to a maximum heating rate coefficient of

$$\alpha_{\max} = \delta^2 \nu_c/12 = 4.2\ 10^5\,\delta^2/\text{sec}. \tag{64}$$

From the examples (63) and (64) it can be seen that the collisionality of the plasma can make a big difference to the efficiency of this heating method. If the plasma is turbulent, particles not only collide among themselves (binary or Coulomb collisions), but also scatter off the fluctuating electric field associated with the turbulence: As a result of this latter process, an anomalous momentum loss occurs, which enhances the collision frequency. These enhanced total collision frequencies have been observed in our laboratory using a method based on broadening of the electron cyclotron absorption resonance.[11] These anomalous momentum losses from the electron population should be equivalent in every way to those arising from binary coulomb (or electron neutral) collisions. This enhanced collision frequency, called the "effective collision frequency," is found to be 10–20 times higher than the binary collision frequency.[11]

IV. FIRST-ORDER HEATING WITH A SAWTOOTH PERTURBATION

The dependence of the heating rate coefficient on the square of the field modulation factor δ constitutes a major

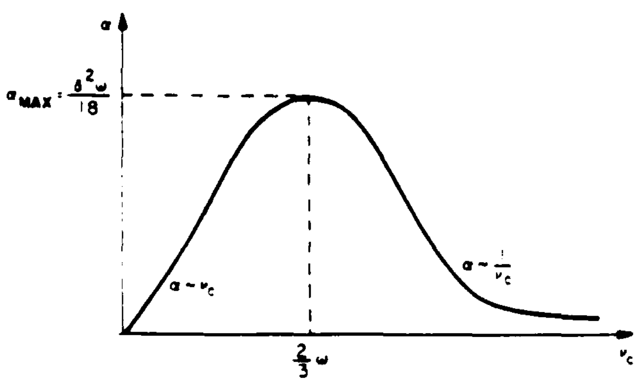

FIG. 3. Heating rate coefficient versus collision frequency.

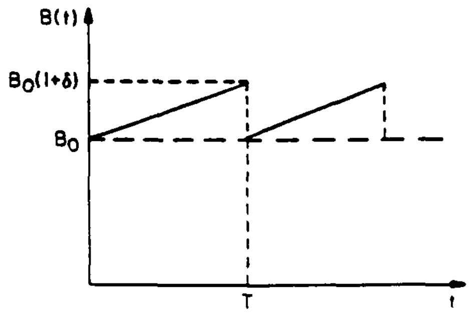

FIG. 4. Magnetic field waveform for a sawtooth perturbation.

disadvantage for the application of a sine wave perturbation: This is because δ is a small number, which makes δ^2 even smaller; therefore, a relatively small energy increase is achieved. In Ref. 9 it was shown that a triangular waveform, with a ramp down that is adiabatic in the sense of preserving the magnetic moment of the particles, also leads to second-order heating by collisional magnetic pumping. A heating rate coefficient proportional to the first power of the field modulation factor would be an improvement. To accomplish this, a perturbation function satisfying Eq. (33) has to be found. Various modulation waveforms for $B(t)$ have been tried: The choice of these had the physical basis that a unidirectional flow of energy had to be maintained, in contrast with the sinusoidal case, where the magnetic field in the heating region is cyclically above and below the background value. This leads to a gain of perpendicular energy in the positive half-cycle and a loss of energy in the negative-half cycle. Any heating is therefore a second-order effect resulting from small differences of large numbers. Also important in the choice of the perturbation function is the ability to pump the plasma adiabatically and repeatedly for periods of time separated by very short durations during which the plasma is not allowed to relax. A sawtooth perturbation has been found to be an answer to the above requirements.

If a sawtooth perturbation is applied, the total magnetic field expression takes the form

$$B = B_0(1 + \delta t/T), \quad \text{for } nT \leqslant t < (n+1)T. \tag{65}$$

For the remainder of this section, the time $t = T^-$ is defined as the time just before the magnetic field sharply decreases $[B(T^-) = B_0(1+\delta)]$ and the time $t = T^+$ is defined as the time at which the magnetic field is equal to its background value B_0. Figure 4 shows the waveform assumed for the magnetic field. The perturbation function is a repetitive ramp with a period equal to $T = T^+$. Since an instantaneous drop of the current generating this perturbation of the magnetic field is not feasible, an appropriate assumption would be that the fall time of the current is shorter than the collision time and is nonadiabatic in the sense that the magnetic moment is not conserved during the drop of the magnetic field.

The differential equation describing the change of energy during the time interval $[0,T]$ is given by

$$\frac{d^2E}{dt^2} + \frac{3}{2}\nu_c\frac{dE}{dt} - \nu_c\frac{\delta/T}{1+\delta t/T}E = 0. \tag{66}$$

The term $(1+\delta t/T)^{-1}$ can be expanded as

$$(1+\delta t/T)^{-1} = 1 - \delta t/T + \cdots . \tag{67}$$

Substituting Eq. (67) into Eq. (66) one obtains

$$\frac{d^2E}{dt^2} + \frac{3}{2}\nu_c \frac{dE}{dt} - \nu_c \frac{\delta}{T}\left(1 + \frac{\delta t}{T} + \cdots\right)E = 0. \tag{68}$$

Retaining only the terms to first order in δ in order to solve for first-order heating, Eq. (68) becomes

$$\frac{d^2E}{dt^2} + \frac{3}{2}\nu_c \frac{dE}{dt} - \nu_c \frac{\delta}{T} E = 0. \tag{69}$$

The solution of Eq. (69) is

$$E(t) + C_1 e^{r_1 t} + C_2 e^{r_2 t}, \tag{70}$$

where r_1 and r_2 are given by

$$r_1 = \tfrac{3}{4}\nu_c\{-1 + [1 + \tfrac{16}{9}(\delta/\nu_c T)]^{1/2}\}, \tag{71}$$

$$r_2 = \tfrac{3}{4}\nu_c\{-1 - [1 + \tfrac{16}{9}(\delta/\nu_c T)]^{1/2}\}. \tag{72}$$

The term $(1 + \frac{16}{9}\delta/\nu_c T)^{1/2}$ can be expanded as

$$[1 + \tfrac{16}{9}(\delta/\nu_c T)]^{1/2} = 1 + \tfrac{8}{9}(\delta/\nu_c T) + \text{higher order terms}. \tag{73}$$

Substituting Eq. (73) into the expressions for r_1 and r_2 and retaining only the first-order terms in δ, we obtain

$$r_1 = \tfrac{2}{3}(\delta/T), \tag{74}$$

$$r_2 = -\tfrac{3}{4}\nu_c[2 + \tfrac{8}{9}(\delta/\nu_c T)]. \tag{75}$$

The initial conditions are given by

$$E(0) = E_0, \tag{76}$$

$$\left.\frac{dE}{dt}\right|_{t=0} = \frac{\delta}{T}\frac{2}{3}E_0. \tag{77}$$

Applying the initial conditions (77) to the expression of $E(t)$ and solving for C_1 and C_2 yields

$$C_1 = E_0, \tag{78a}$$

$$C_2 = 0. \tag{78b}$$

The solution of Eq. (69) subject to the initial conditions (78a) and (78b) is

$$E(t) = E_0 e^{(2/3)\delta(t/T)}. \tag{79}$$

This solution is only good in the time interval $0 \leqslant t < T$ and for $\delta/\nu_c T \ll 1$. At $t = T^-$, the energy is

$$E \sim E_0 e^{(2/3)\delta} \sim E_0(1 + \tfrac{2}{3}\delta), \tag{80}$$

which yields

$$\Delta E = E(T^-) - E(0) = \tfrac{2}{3}\delta E_0. \tag{81}$$

Now let us examine what happens to the energy during the sharp fall of the magnetic field between T^- and T^+. During this time, the assumption of the constancy of the adiabatic invariant may be violated; thus we have

$$\frac{d\mu}{dt} = \frac{1}{B}\frac{dE_\perp}{dt} - \frac{E_\perp}{B^2}\frac{dB}{dt}. \tag{82}$$

Equation (82) can be written as

$$\frac{dE_\perp}{dt} = \mu\frac{dB}{dt} + B\frac{d\mu}{dt}. \tag{83}$$

Since no collisions occur between T^- and T^+, we have

$$\frac{dE_\parallel}{dt} = 0. \tag{84}$$

Summing Eqs. (83) and (84), we obtain

$$\frac{dE}{dt} = \mu\frac{dB}{dt} + B\frac{d\mu}{dt}. \tag{85}$$

Equation (85) can also be written as

$$\frac{\Delta E}{\Delta t} + \mu\frac{\Delta B}{\Delta t} + B\frac{\Delta\mu}{\Delta t} \tag{86}$$

or

$$\Delta E = \mu\Delta B + B\Delta\mu. \tag{87}$$

The change in magnetic moment $\Delta\mu$ is given by

$$\Delta\mu = \mu(T^+) - \mu(T^-), \tag{88}$$

with

$$\mu(T^-) = E_\perp(T^-)/B_0(1+\delta), \tag{89}$$

$$\mu(T^+) = E_\perp(T^+)/B_0. \tag{90}$$

Since no collisions occur between T^- and T^+, we assume that no appreciable change in the perpendicular energy occurs. Thus we have

$$E_\perp(T^+) \simeq E_\perp(T^-) = (1+\delta)E_\perp(0). \tag{91}$$

As a result of equipartition we have

$$E_\perp(0) = \tfrac{2}{3}E_0,$$

which yields

$$\Delta\mu = \tfrac{2}{3}\delta(E_0/B_0). \tag{92}$$

Inserting Eq. (92) into Eq. (87) and substituting ΔB by $(-\delta B_0)$ we obtain

$$\Delta E = -\mu(T^-)\delta B_0 + B(T^-)\tfrac{2}{3}\delta(E_0/B_0). \tag{93}$$

Using the facts that

$$\mu(T^-) = \tfrac{2}{3}(E_0/B_0), \tag{94}$$

$$B(T^-) = (1+\delta)B_0, \tag{95}$$

Eq. (93) becomes

$$\Delta E = \tfrac{2}{3}\delta^2 E_0. \tag{96}$$

Summing Eqs. (96) and (81) the energy increase per cycle is found to be

$$\Delta E = \tfrac{2}{3}\delta(1+\delta)E_0. \tag{97}$$

Since $\delta \ll 1$, Eq. (97) can be approximated as

$$\Delta E = \tfrac{2}{3}\delta E_0. \tag{98}$$

The heating rate dE/dt is given by

$$\frac{dE}{dt} = \frac{\delta\omega}{3\pi}E_0, \tag{99}$$

where the period of the sawtooth is taken as $T = 2\pi/\omega$.

Equation (99) suggests that first-order heating is achievable with a sawtooth perturbation and that the heating rate is independent of the collision frequency.[9] This is an interesting result and of key importance for fusion machines, where the mean free path is larger than the plasma length.

To check this result, the generalized theory for first-order heating already presented is applied.[9] Substituting

$f'(t)$ by its value for a sawtooth perturbation in Eq. (36) yields the value of the coefficient l_1:

$$l_1 = \omega/3\pi. \tag{100}$$

Using Eq. (39), the heating rate is found to be

$$\frac{dE}{dt} = \delta l_1 E_0 = \frac{\delta\omega}{3\pi} E_0 = \beta E_0, \tag{101}$$

where β is the heating rate coefficient given by

$$\beta = \delta\omega/3\pi. \tag{102}$$

Equation (102) is in agreement with the result of Eq. (99).[9] The independence of Eq. (102) of the collision frequency is a consequence of the collisionless "resetting" of the magnetic induction during the sudden drop on the trailing edge of the sawtooth in Fig. 4. This effect allows the perpendicular energy to increase linearly in time without a decrease associated with the decreasing magnetic field. This perpendicular energy will be carried to the parallel components as long as there are any collisions at all. Thus the drop at the trailing edge of the sawtooth need not be so fast as to be nonadiabatic in the sense of violating the constancy of μ; the drop-off time can be any duration shorter than the collision time.

V. COMPARISON BETWEEN FIRST-ORDER COLLISIONAL MAGNETIC PUMPING AND OTHER PLASMA HEATING METHODS

In order to have a quantitative idea of how beneficial it is to achieve first-order heating by collisional magnetic pumping, we have to answer the following question: How does this heating rate compare to other plasma heating methods?

First, let us compare the two heating rate coefficients obtained when sinusoidal and sawtooth perturbations are applied to collisional magnetic pumping. For this, the ratio of the two coefficients given by Eq. (102) and the inverse of (58) is taken to be

$$\beta/\alpha = (\delta\omega/3\pi)\left[6(\tfrac{9}{4}\nu_c^2 + \omega^2)/\delta^2\omega^2\nu_c\right], \tag{103}$$

where β and α are, respectively, the heating rate coefficients for a sawtooth and a sinusoidal perturbation. Assuming that the rf driving frequency and the field modulation factor δ are the same for both cases the ratio (103) becomes

$$\beta/\alpha = (\tfrac{9}{2}\nu_c^2 + 2\omega^2)/\pi\delta\omega\nu_c. \tag{104}$$

If the plasma is highly collisional, we have $\nu_c \gg \omega$ and Eq. (104) becomes

$$\beta/\alpha = (9/2\pi)(\nu_c/\delta\omega). \tag{105}$$

The ratio (105) is much larger than unity. For a small δ and a large collision frequency to driving frequency ratio, β can be as much as three orders of magnitude larger than α.

If the plasma is "collisionless," we have $\omega \gg \nu_c$ and Eq. (104) becomes

$$\beta/\alpha = (2/\pi)(\omega/\delta\nu_c). \tag{106}$$

As in case (105) the ratio (106) is much larger than unity; for a small value of δ and a large ω/ν_c, β can be two or three orders of magnitude larger than α.

The ratio β/α is minimum when $\omega = (3/2)\nu_c$, and it is given by

$$\beta/\alpha = 6/\pi\delta. \tag{107}$$

Equation (107) is still a number greater than 1. For a field modulation factor of 1%, we have

$$\beta = 191\,\alpha. \tag{108}$$

It therefore appears that in all cases first-order heating is an improvement on second-order heating. First-order heating provides a heating rate coefficient at least one order of magnitude larger than otherwise possible with second-order heating.

Ion or electron cyclotron resonant heating is one of the most efficient and widely used heating methods in fusion experiments: The maximum energy increase per cyclotron period obtained by this method is given by[6]

$$\Delta E_\perp = \pi E(2mE_\perp)^{1/2}/B_0, \tag{109}$$

where E is the electric field amplitude of the wave, B_0 is the background magnetic field, and $E_\perp$ is the perpendicular component of the energy whose equipartitioned value is equal to 2/3 of the total energy. The energy increase rate is given by

$$\gamma = \Delta E_\perp/\tau_c = qE(E_\perp/2m)^{1/2}, \tag{110}$$

where τ_c is the cyclotron period given by

$$\tau_c = 2\pi m/qB. \tag{111}$$

To compare the energy increase rate (110) to the one obtained by first-order heating with collisional magnetic pumping, their ratio is taken to be

$$\beta E_0/\gamma = [\delta\omega(2m)^{1/2}/3\pi qE](E_0/E_\perp^{1/2}). \tag{112}$$

To acquire a quantitative idea of the ratio (112), consider the following characteristic values of the plasma parameters: Let $\omega = 2\pi 10^7$ rad/sec, $\delta = 10^{-2}$, $E = 100$ V/cm, $E_0 = 1$ keV, and the plasma consists of helium ions. The value of $\beta E_0/\gamma$ is

$$\beta E_0/\gamma = 7.45\%.$$

Keeping in mind that the ratio (112) is taken for the maximum value that the ICRH (ion cyclotron resonance heating) rate γ can reach, it can be concluded that first-order collisional magnetic pumping is a heating method that may be competitive with other widely used methods such as ICRH.

VI. CONCLUSION

The equations describing the rate of change of the energy of the particles in a plasma adiabatically pumped with collisional magnetic pumping are presented. A general solution for first-order heating along with particular solutions to the energy increase rate for two specific magnetic field perturbations are derived.

When a sinusoidal perturbation is superimposed on the background magnetic field, a heating rate proportional to the second power of the field modulation factor δ is obtained. This is in agreement with the results of Schluter[2] and Berger et al.[3] This heating rate is also strongly dependent on the collisionality of the plasma. A maximum heating rate is

achieved when the driving rf frequency is 1.5 times larger than the collision frequency.

The application of a sinusoidal perturbation has two major drawbacks. The first drawback is the dependence of the heating rate on the second power of the field modulation factor δ, this number is less than unity and its square is even smaller. The second drawback is the strong dependence of the heating rate on the collision frequency. This is especially disadvantageous for a fusion-grade plasma, where the mean free path is larger than the plasma length. These two drawbacks result in a small energy increase rate. In the past, these factors apparently led researchers to neglect this heating method.

In the search for more satisfactory results, a heating rate proportional to the first power of the field modulation factor and weakly dependent on the collision frequency was needed. A sawtooth perturbation proved to be an appropriate choice. The heating rate for this case is two to three orders of magnitude larger than that for second-order heating and is comparable to other widely used plasma heating methods. An experimental demonstration of this first-order heating has been presented elsewhere.[9]

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Computational Treatment of Collisional Magnetic Pumping

M. Laroussi[a] and J. Reece Roth
The University of Tennessee, Knoxville
Department of Electrical and Computer Engineering
Knoxville, Tennessee 37996-2100

Abstract

When collisional magnetic pumping is applied to a plasma, the heating rate depends strongly on the nature of the waveform of the magnetic perturbation, whether sinusoidal, triangular, or sawtoothed in time. Numerical solutions to the energy transfer problem are obtained when these waveforms are applied to heat a plasma, and compared with previously obtained analytical results using small perturbation theory where these results are available. A specially written Fortran program computes the numerical values of the parallel, perpendicular, and total energy at each time increment. The plasma heating rates and optimum heating conditions derived from this study are in good agreement with analytical limiting cases and available experimental data, except when the perturbation amplitude becomes large enough that the analytical results no longer hold.

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[a]Present Address: Department of Electrical Engineering, Technical University, Sfax, Tunisia

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I. Introduction

Magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_0(1 + \delta f(t))$, where B_0 is the uniform steady state background magnetic field, δ is the field modulation factor defined as $\delta = \Delta B/B_0$, and $f(t)$ is a periodic function of time. Contrary to ohmic heating, where the electric field is parallel to the confining axial magnetic field, in magnetic pumping the oscillating electric field is produced by variation of the axial magnetic field and thus is perpendicular to it. This type of heating was called "magnetic pumping" due to the existence of a compressional wave perpendicular to the background magnetic field, causing the plasma to be cyclically compressed and relaxed by an alternating E x B force. Under favorable conditions, the mechanical energy exerted by the compressing force would ultimately be absorbed by the plasma and lead to a heating of the charged particles.

Depending on how plasma parameters and the driving force relate to each other, different heating regimes are obtained. In the case of collisional magnetic pumping, which is the main interest of this paper, the collisions are the mediator between the RF field and the charged particles. To achieve heating by collisional magnetic pumping, the charged particles should collide before leaving the heating region. Mathematically, the following inequalities have to be satisfied:

$$\omega_{tr} << v_c \sim \omega << \omega_{cy}.$$

Where ω_{tr}, v_c, ω, and ω_{cy} are respectively the transit frequency through the heating region, the collision frequency, the RF field frequency, and the particle gyrofrequency.

Magnetic pumping was first suggested as a heating method (for the Stellarator-C) by Spitzer and Witten in 1953[1]. A theoretical analysis was published by Schluter[2], and also by Berger et al.[3] a few years later. These papers constitute most of the very limited early literature on this subject. This was so because heating by magnetic pumping was first part of a classified project, and later was neglected due to the attention given to other more promising heating methods, such as ion-cyclotron resonance heating. After a fallow period of nearly thirty years, there has been a revival of interest in this heating method.[4-9] This interest is a result of the demonstration that heating proportional to the field modulation factor, δ, rather than its square is possible. This enhanced heating rate can be comparable with other RF-based methods, such as ion-or electron cyclotron resonance heating[4-9].

II. Available Analytical Results

The process of energy transfer between the RF field and the charged particles has been studied analytically, starting from the assumption that for a magnetic field slowly varying in time and space, the magnetic moment (defined as the ratio of the perpendicular component of the kinetic energy to the magnetic field) is a constant of the motion. It can be shown[2-7] that a general equation relating the change in the total energy of a particle to the change of the magnetic field can be derived. This equation is

$$\frac{d^2E}{dt^2} - \left[-\frac{3}{2} v_c + \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1} \right] \frac{dE}{dt} - \frac{v_c}{B} \frac{dB}{dt} E = 0. \tag{1}$$

This homogeneous, linear, second order differential equation has periodic coefficients which can go to infinity periodically. Such equations usually

appear in astronomical studies, and their general solution was given by the French mathematician G. Floquet.[10] Using Floquet's theory and a perturbation treatment, Schluter[2] and Berger et al.[3] derived the energy increase rate when a sinusoidal perturbation is applied. The energy can be written in terms of the collisionality parameter $v_c T$, where $T = 2\pi/\omega$ is the period of the periodic perturbation, and $v_c T$ itself is the number of collisions per field period. The energy increase rate for a sinusoidal perturbation is

$$\Delta E = \delta^2 E_o \frac{2\pi^2 v_c T}{3\left(\frac{9}{4} v_c^2 T^2 + 4\pi^2\right)} \quad \text{eV/cycle}, \tag{2}$$

where δ is the field modulation factor, and E_o is the initial energy in electron volts. The analytical heating rates are all a function of the initial energy E_o because Eq. 1 is a statement about the thermally adiabatic heating rate, and not about a complete energy balance of the plasma. In a steady-state complete energy balance, the plasma particles would lose the "memory" of their initial energy, in favor of the prevailing kinetic temperature.

The optimum collisionality parameter, at which the energy increase rate is a maximum, is

$$v_c T = \frac{4\pi}{3} \quad \text{collisions/cycle}, \tag{3}$$

and the value of this maximum energy increase rate is

$$(\Delta E)_{max} = \delta^2 E_o \frac{\pi}{9} \quad \text{eV/cycle}. \tag{4}$$

For a highly collisional plasma, $v_c T >> 1$, and the energy increase rate can be approximated

$$\Delta E \approx \delta^2 E_o \frac{8\pi^2}{27} \times \frac{1}{v_c T} \quad \text{eV/cycle}, \tag{5}$$

while for a relatively collisionless plasma, $v_c T << 1$, and the energy increase rate becomes

$$\Delta E \approx \delta^2 E_o \cdot \frac{v_c T}{6} \quad \text{eV/cycle} . \tag{6}$$

These energy increase rates are valid for small magnetic field perturbations $\delta << 1$. The upper limit of the validity of these expressions can best be

determined by computational investigation of Equation 1 with a sinusoidal magnetic perturbation.

Equation 1 has recently been solved for the general case in which an arbitrary periodic perturbation function f(t) is assumed.[4,5,7] A condition for the achievement of a heating rate proportional to the <u>first</u> power of the field modulation factor, δ, has been derived[5,7]. It is found that a sawtooth perturbation satisfies the condition for first order heating, and the energy increase rate for this case is

$$\Delta E = \frac{2}{3}\,\delta E_o \quad \text{eV/cycle} \tag{7}$$

For this case, the energy increase rate for $\delta << 1$ is independent of the collisionality parameter, and is two or three orders of magnitude larger than the energy increase rate of the sinusoidal perturbation giving rise to Equation 2. Over what range of δ this improved heating might prove valid is, again, best determined with a computational investigation of a sawtooth waveform in Equation 1.

III. <u>Computational Analysis</u>

The theoretical treatment of collisional magnetic pumping[1-5] provides us with small perturbation solutions to the energy increase rate and how it relates to the collisionality of the plasma. However, this approach fails to give a quantitative picture of the evolution of the energy with time from the instant that collisional magnetic pumping is turned on, and also fails to give insight into the conditions for which this small perturbation solution is no longer valid. For this purpose, a numerical solution to the energy transfer equation is sought. This solution provides us with numerical values of the

energy for each time increment. This series of numbers can be plotted on an energy-time diagram. The energy increase rate can be easily extracted from such a diagram and compared with the analytical prediction discussed above.

The equations describing the variations of the parallel and perpendicular components of the energy are given by[5,7]

$$\frac{dE_{\parallel}}{dt} = v_c\left(\frac{E_{\perp}}{2} - E_{\parallel}\right), \tag{8}$$

and

$$\frac{dE_{\perp}}{dt} = \frac{E_{\perp}}{B}\frac{dB}{dt} - v_c\left(\frac{E_{\perp}}{2} - E_{\parallel}\right). \tag{9}$$

Since the total energy is the sum of $E_{\parallel}$ and $E_{\perp}$, we also have

$$\frac{dE}{dt} = \frac{dE_{\parallel}}{dt} + \frac{dE_{\perp}}{dt}. \tag{10}$$

The magnetic field is given by

$$B = B_o(1 + \delta f(t)), \tag{11}$$

which gives

$$\frac{1}{B}\frac{dB}{dt} = \frac{\delta f'(t)}{1 + \delta f(t)}. \tag{12}$$

Let

$$E_{\parallel} = x,$$

$$E_{\perp} = y,$$

and

$$F(t) = \frac{\delta f'(t)}{1 + \delta f(t)}.$$

Equations (8) and (9) can be written as

$$\frac{dx}{dt} = -v_c x + 0.5\, v_c y, \tag{13}$$

and

$$\frac{dy}{dt} = -v_c x - 0.5\, v_c y + y\, F(t), \tag{14}$$

For a given value of the collision frequency, v_c, a perturbation function f(t), and initial value x_0 and y_0, numerical values of x and y are computed and tabulated for each time step. A plotting routine furnishes the plots of x vs t and y vs t. The total energy is also plotted as $z = x + y$. The Fortran program used has the flexibility of entering the values of the collision frequency, v_c, the period of the RF waveform, T, the field modulation factor, δ, the initial values of the energy components, the total energy of the particles in electron volts, and the time step size. The y-axis of the plots represents energy in electron-volts and the x-axis represents time in units of the period of the RF waveform, T. The number of periods plotted can be changed, allowing one to follow the evolution of the energy far enough in time to observe any transient period, along with any steady state reached. This program is available as an appendix to reference 7, or from the authors.

Three waveforms have been studied. These are a sinusoidal waveform, a triangular waveform, and a sawtooth waveform. These waveforms can be, or have been, implemented experimentally[7,9]. This not only allows a comparison between theory and experiment, but also gives a sense of practicality to this work. Since the collision frequency and how it relates to the RF frequency is an important parameter that affects the heating rate, we define a *collisionality parameter*, v_cT, given by the product of the collision frequency and the period of the RF wave. The collisionality parameter is a dimensionless number which indicates how many collisions occur during one RF period. By varying v_cT, different regimes are obtained and the resulting heating rates are computed from the plots of the energy versus time.

IV. Application to a Sinewave

When a sinewave perturbation is applied, results similar to those first considered by Schluter[2] and Berger et al.[3] should be obtained. Fig. 1 shows the waveform of the magnetic field assumed. For a "collisionless" plasma ($v_cT = 0.2$), shown in Figures 2 and 3, the total energy of a particle oscillates with the field with only a very small increase in its average value. This is consistent with the lack of energy transfer between the parallel and perpendicular components of the energy. For this case, the values of the field modulation factor, δ, and of the initial energy, E_0, are chosen to be respectively 0.1 and 300 eV. Fig. 2 shows that after a transient period of about 12T, where T is the period of the driving RF waveform, the parallel component of the energy reaches a plateau at a level less than its initial value. This is a phase-dependent effect, and averages out to the initial value over all initial phase angles for f(t). For a collisional plasma ($v_cT = 6$), Fig. 4 and Fig. 5 show that the average value of the energy increases with time at a rate of about 0.85 eV/cycle, if $E_0 = 300$ eV and $\delta = 0.10$.

In Fig. 6, the energy increase rate is plotted against the collisionality parameter, v_cT, at a field modulation factor of $\delta = 0.1$ and an inital value of the energy of 300eV. The solid dots represent analytical results from Eq. 2, while the triangles represent the computational results obtained from energy plots similar to Figs. 2 to 5. The results show good agreement with the analytical prediction. The energy increase rate is peaked, with a maximum at an optimum value of the collisionality parameter of about 4.2, in agreement with Eq. 3.

Fig. 7 is a plot on a log-log scale, of the energy increase rate as a function of the field modulation factor for several values of the collisionality parameter, and an initial value of the energy of 300eV. A slope of 2 indicates that the energy increase rate is proportional to the second power of the field modulation factor, δ^2, also in agreement with Eq. 2. The small perturbation approximation represented by Eq. 2 is good out to at least a field modulation factor of $\delta = 0.40$.

V. Application to a Triangular Waveform

A triangular waveform of adjustable shape was selected to study collisional magnetic pumping computationally, because it is a general case, one limit of which is a sawtooth waveform. Fig. 8 shows the magnetic field when a triangular perturbation is applied. If the ramping down time, (T-L), is gradually reduced until it becomes zero, a transition to a sawtooth waveform is achieved. This allows one to write a simple algorithm capable of showing the change in the energy waveform when the transition between triangular and sawtooth waveforms occurs.

First, a symmetrical triangular waveform with $L = T/2$ and a collisional case is applied by setting the collisionality parameter, $\nu_c T$, equal to 10. This implies ten collisions per field period. A field modulation factor, δ, of 0.1 is chosen. As seen in Fig. 9 through Fig. 11, the parallel, perpendicular, and total energy oscillate with the field but their average values increase with time. The total energy increase per cycle for a particle with an initial energy of 300 eV is about 0.12 eV. This compares with about 0.75 eV/cycle predicted by Eq. 2 for the sinusoidal case.

Now if the collisionality parameter is equal to 0.1, a low collisionality case is obtained for which one collision occurs each ten field periods (see Figs. 12 to 14). As shown in Fig. 14, the total energy oscillates with the field, but its average value does not increase significantly with time. The explanation of this can be seen in Fig. 12, which shows the parallel component of the energy as a function of time. For a transient period lasting approximately 15T, where T is the period of the driving RF waveform, the parallel energy increases, but soon reaches a saturation plateau. As the field pumps the plasma further, no energy transfer between the perpendicular component of the energy and its parallel component occurs, which results in zero energy gain. For the sinusoidal perturbation, Eq. 2 predicts a small heating rate of 0.05 eV/cycle, which may be too small to be apparent on Fig. 14.

Setting the collisionality parameter equal to 20, an energy increase is also obtained, but of smaller magnitude than the $v_c T = 10$ case. This, with the data in Figs. 9 to 14, indicates that the energy increase rate has a maximum at some optimum value of the collisionality parameter. Fig. 15 shows a plot of the energy increase rate versus collisionality parameter at a field modulation factor of $\delta = 0.1$, and an initial value of the energy of $E_0 =$ 300eV. The maximum energy increase rate is very close to the collisionality parameter of $v_c T = 4\pi/3$ predicted by Eq. 3 for the sinusoidal perturbation case; the maximum value of the energy increase rate in Figure 15, $\Delta E \approx 0.17$ eV/cycle, is well below the maximum value of $\Delta E = 1.05$ eV/cycle predicted by Equation 4 for the sinusoidal driving waveform.

The energy increase rate has been plotted in Figure 16 against the field modulation factor on a log-log scale for several values of the collisionality

parameter. For all values of the collisionality parameter, it has been found from solutions similar to Figs. 9 to 14, that the energy increase rate is proportional to the second power of the field modulation factor. This dependence holds at least up to $\delta = 0.50$. The above analysis has been done for several non-zero ramping down times but no quantitative effects on the energy increase rate have been observed.

VI. Application to a Sawtooth Waveform

When a sawtooth perturbation is applied to collisional magnetic pumping, the magnetic field assumes the waveform shown in Fig. 17. Many collisionality regimes have been tried but the energy increase rate was independent of the collisionality parameter, as predicted by Eq. 7. Contrary to the triangular and sinusoidal waveform cases, the energy does not oscillate, but keeps increasing with time, at a rate of 20eV/cycle when a particle of 300eV initial energy and a field modulation factor, δ, of 0.10 are assumed. This linear increase is a consequence of a nonadiabatic effect during the sharp drop-off at the trailing edge of the waveform[5,7]. Fig. 18 through Fig. 20 show the behavior with time of the parallel, perpendicular, and total energy for a collisionless plasma ($v_c T = 0.2$). Fig. 21 shows the total energy versus time for a collisional plasma ($v_c T = 6$).

The energy increase rate versus the collisonality parameter is plotted in Fig. 22, for a field modulation factor of 0.01 and an initial energy of 300eV. The solid dots represent the analytical results predicted by Equation 7, and the triangles represent computational results obtained from the energy plots. These results are in excellent agreement, and confirm the fact that the energy

increase rate is independent of the plasma collisionality for the sawtooth driving waveform.

A log-log plot of the energy increase rate versus the field modulation factor, δ, is shown in Fig. 23. It shows that for $\delta \leq 0.20$, the relationship is linear with a slope near 1, but for $\delta > 0.20$ the slope is no longer unity (it is about 2.27). This is consistent with the analytical result of Eq. 7, which predicts first order heating only for small field modulation factors. Figure 23 indicates that the small perturbation assumption on which Eq. 7 is based breaks down above $\delta = 0.20$. Figure 23 also indicates that for large field modulation factors, $\delta > 0.20$, the heating rate reverts to the second order (δ^2) dependence characteristic of a sinusoidal perturbation, but with an amplitude about 15 times that predicted by Eq. 4, the highest possible heating rate for small sinusoidal perturbations.

VII. Conclusions

The above analysis shows that the plasma collisionality plays an important role in the viability of collisional magnetic pumping as a plasma heating method if sinewave or triangular perturbing waveforms are used. It also confirms that the heating rate is proportional to the square of the field modulation factor, δ, for these waveforms, when this modulation factor is much less than unity. This was predicted analytically for the sinusoidal waveform[1-5]. To achieve the best heating performance in these cases, operation at an optimum collisionality is required. The optimum collisionality parameter, $\nu_c T$, is $4\pi/3$ for both the sinusoidal and triangular waveforms. Away from this maximum, the energy increase rate falls off

rapidly, leading to lower heating performance. The triangular waveform appears to heat less well by a factor of 5 or more than the sinusoidal waveform, as indicated by a comparison of Figures 6 and 15.

The computational analysis shows that the energy increase rate is indeed independent of the collisionality parameter when a sawtooth perturbation is applied. It also confirms that first order heating is achievable for small values of the field modulation factor, less than 0.20. The energy increase rate in this case is many orders of magnitude larger than the one obtained when a sinusoidal perturbation is used. Experimental implementation of heating with the sawtoothed waveform is described elsewhere[7-9]

Acknowledgement

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Figure Captions

Fig. 1 Magnetic field waveform for a sinusoidal perturbation.

Fig. 2. Parallel component of the energy versus time for $\delta = 0.1$, $v_c T = 0.2$, $E_o = 300$ eV, and a sinusoidal perturbation.

Fig. 3 Total energy versus time for $\delta = 0.1$, $v_c T = 0.2$, $E_o = 300$ eV, and a sinusoidal perturbation.

Fig. 4 Parallel component of the energy versus time for $\delta = 0.1$, $v_c T = 6$, $E_o = 300$ eV, and a sinusoidal perturbation.

Fig. 5 Total energy versus time for $\delta = 0.1$, $v_c T = 6$, $E_0 = 300$ eV, and a sinusoidal perturbation.

Fig. 6 Energy increase rate versus collisionality parameter for $\delta = 0.1$, Eo = 300 eV, and a sinusoidal perturbation.

Fig. 7 Energy increase rate versus field modulation factor for $E_o = 300$ eV, several collisionality parameters, and a sinusoidal perturbation.

Fig. 8 Magnetic field waveform for a triangular perturbation.

Fig. 9 Parallel component of the energy versus time for $\delta = 0.1$, $v_c T = 10$, $E_o = 300$ eV, and a triangular perturbation.

Fig. 10 Perpendicular component of the energy versus time for $\delta = 0.1$, $v_c T = 10$, $E_o = 300$ eV, and a triangular perturbation.

Fig. 11 Total energy versus time for $\delta = 0.1$, $v_c T = 10$, $E_o = 300$ eV, and a triangular perturbation.

Fig. 12 Parallel component of the energy versus time for $\delta = 0.1$, $v_c T = 0.1$, $E_0 = 300$ eV, and a triangular perturbation.

Fig. 13 Perpendicular component of the energy versus time for $\delta = 0.1$, $v_c T = 0.1$, $E_o = 300$ eV, and a triangular perturbation.

Fig. 14 Total energy versus time for $\delta = 0.1$, $v_c T = 0.1$, $E_0 = 300$ eV, and a triangular perturbation.

Fig. 15 Energy increase rate versus collisionality parameter for $\delta = 0.1$, $E_0 = 300$ eV, and a triangular perturbation.

Fig. 16 Energy increase rate versus field modulation factor for $E_0 = 300$ eV, several collisionality parameters, and a triangular perturbation.

Fig. 17 Magnetic field waveform for a sawtooth perturbation.

Fig. 18 Parallel component of the energy versus time for $\delta = 0.01$, $v_c T = 0.2$, $E_0 = 300$ eV, and a sawtooth perturbation.

Fig. 19 Perpendicular component of the energy versus time for $\delta = 0.01$, $v_c T = 0.2$, $E_0 = 300$ eV, and a sawtooth perturbation.

Fig. 20 Total energy versus time for $\delta = 0.01$, $v_c T = 0.2$, $E_0 = 300$ eV, and a sawtooth perturbation.

Fig. 21 Total energy versus time for $\delta = 0.01$, $v_c T = 6$, $E_0 = 300$ eV, and a sawtooth perturbation.

Fig. 22 Energy increase rate versus collisionality parameter for $\delta = 0.01$, $E_0 = 300$ eV, and a sawtooth perturbation.

Fig. 23 Energy increase rate versus field modulation factor for $E_0 = 300$ eV and a sawtooth perturbation.

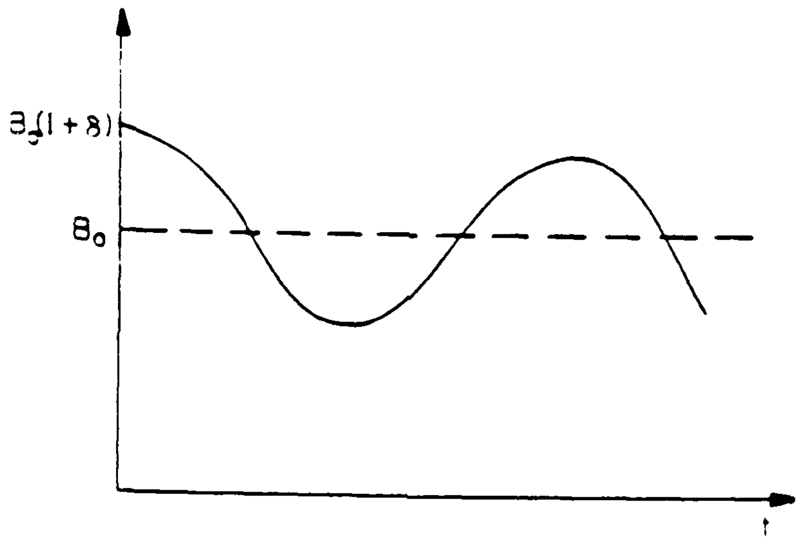

Fig. 1 Magnetic field waveform for a sinusoidal perturbation.

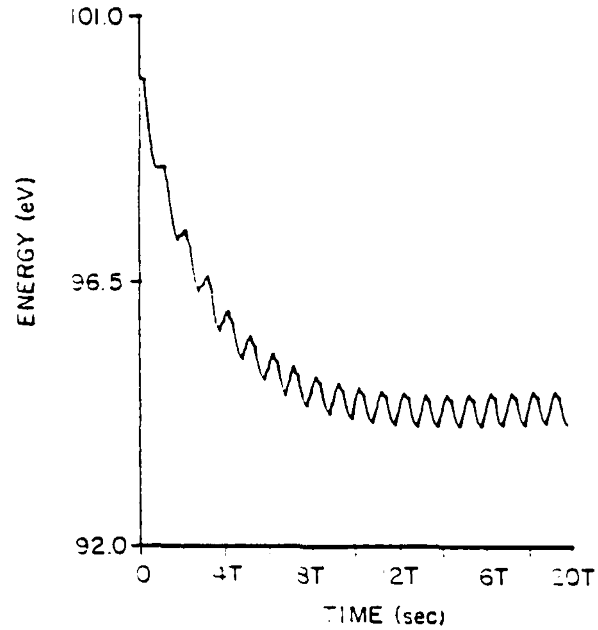

Fig. 2. Parallel component of the energy versus time for $\delta = 0.1$, $v_c T = 0.2$, $E_0 = 300$ eV, and a sinusoidal perturbation.

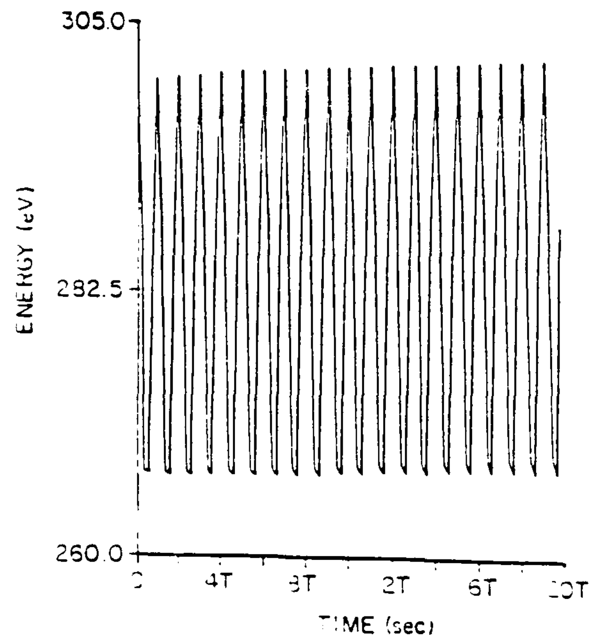

Fig. 3 Total energy versus time for $\delta = 0.1$, $v_c T = 0.2$, $E_0 = 300$ eV, and a sinusoidal perturbation.

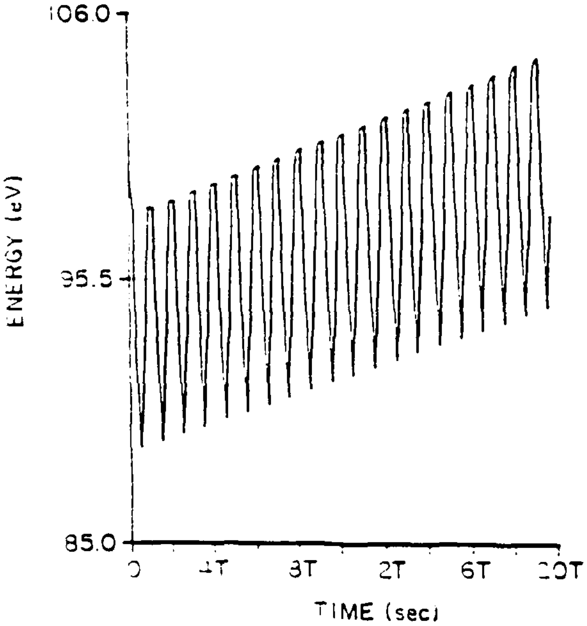

Fig. 4 Parallel component of the energy versus time for $\delta = 0.1$, $v_c T = 6$, $E_o = 300$ eV, and a sinusoidal perturbation.

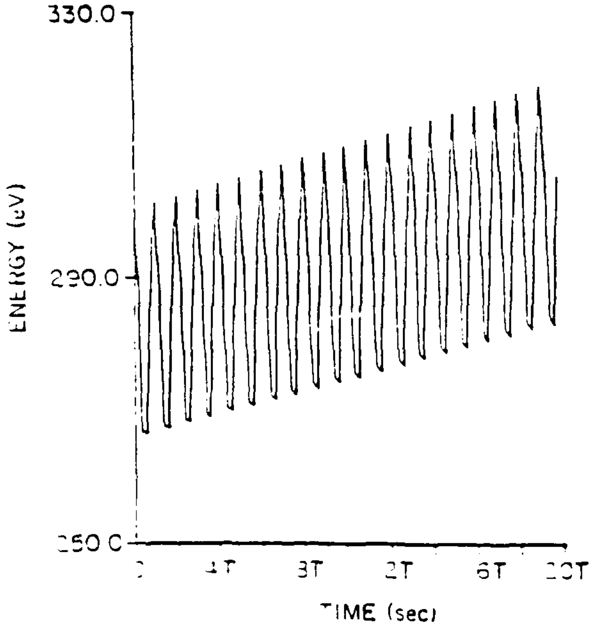

Fig. 5 Total energy versus time for $\delta = 0.1$, vc T = 6, Eo = 300 eV, and a sinusoidal perturbation.

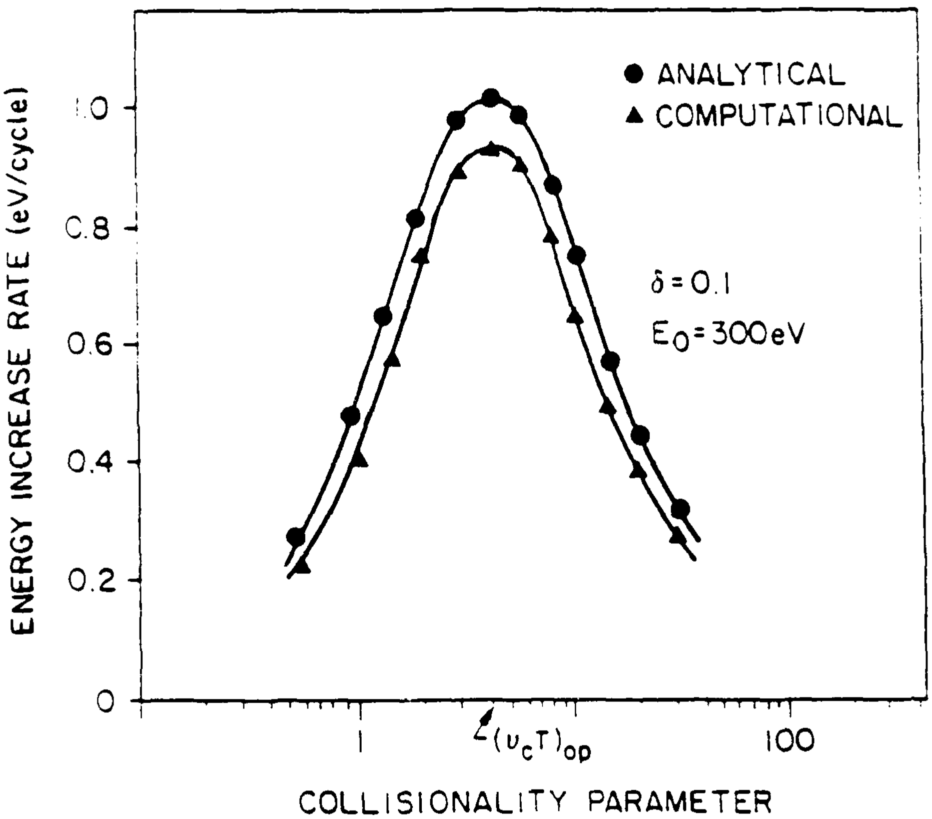

Fig. 6 Energy increase rate versus collisionality parameter for $\delta = 0.1$, $E_0 = 300$ eV, and a sinusoidal perturbation.

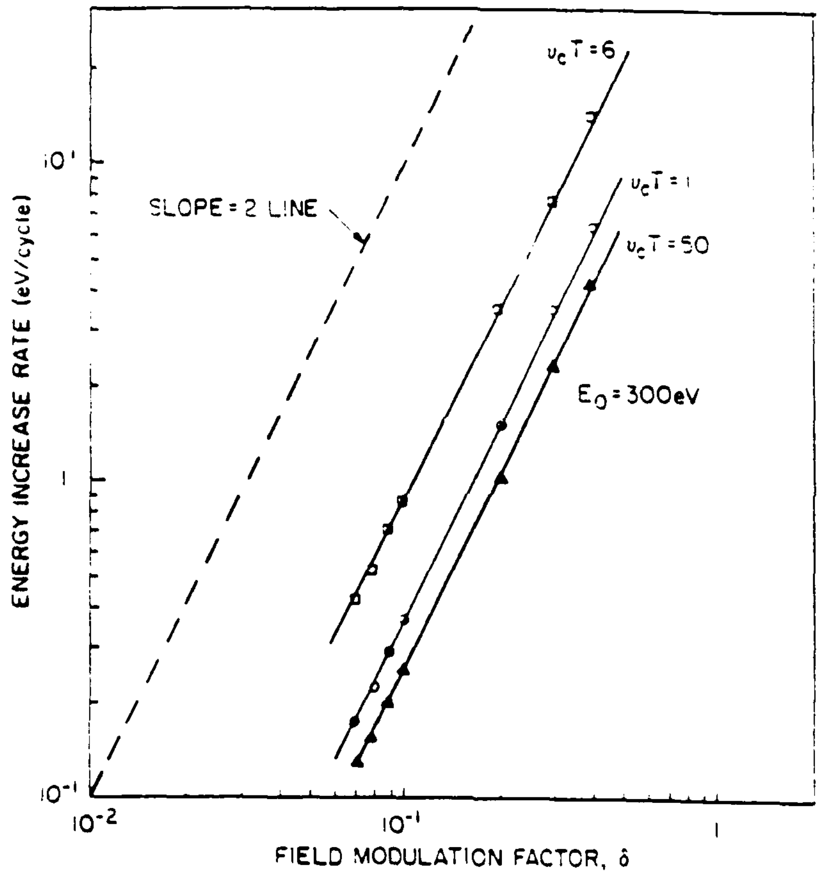

Fig. 7 Energy increase rate versus field modulation factor for E_o = 300 eV, several collisionality parameters, and a sinusoidal perturbation.

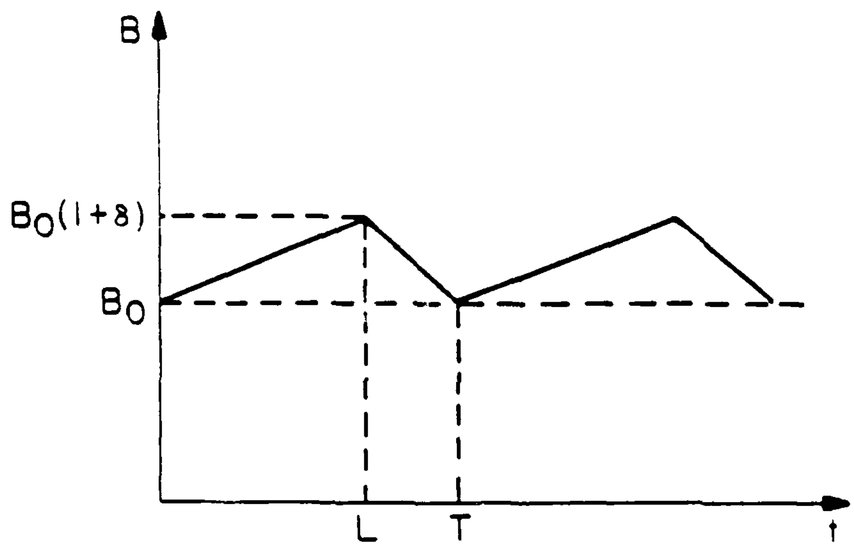

Fig. 8 Magnetic field waveform for a triangular perturbation.

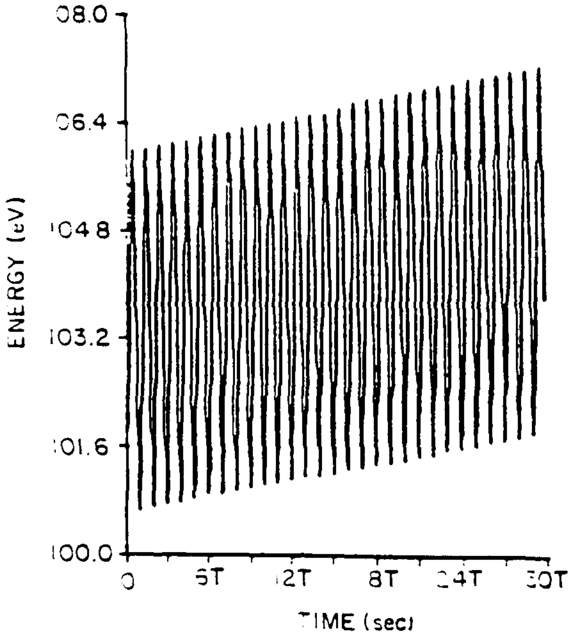

Fig. 9 Parallel component of the energy versus time for $\delta = 0.1$, $v_c T = 10$, $E_0 = 300$ eV, and a triangular perturbation.

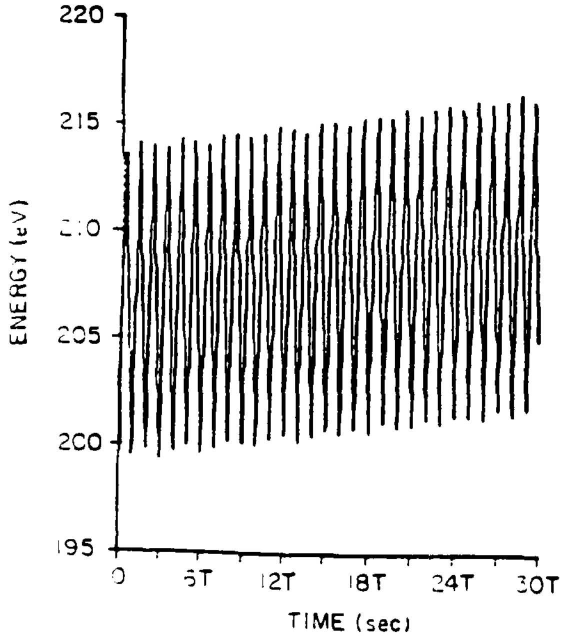

Fig. 10 Perpendicular component of the energy versus time for $\delta = 0.1$, $v_c T = 10$, $E_0 = 300$ eV, and a triangular perturbation.

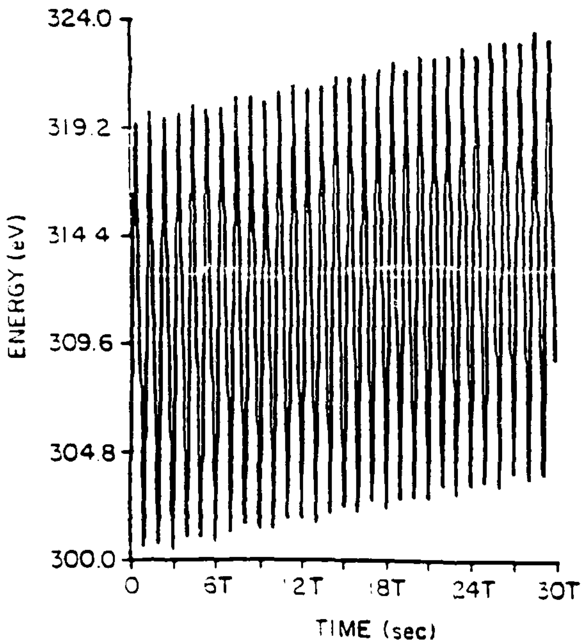

Fig. 11 Total energy versus time for $\delta = 0.1$, $v_c T = 10$, $E_0 = 300$ eV, and a triangular perturbation.

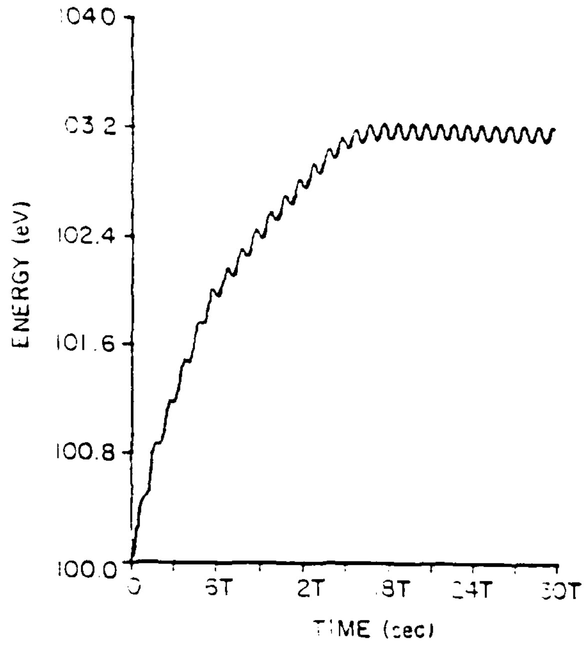

Fig. 12 Parallel component of the energy versus time for $\delta = 0.1$, $v_c T = 0.1$, $E_0 = 300$ eV, and a triangular perturbation.

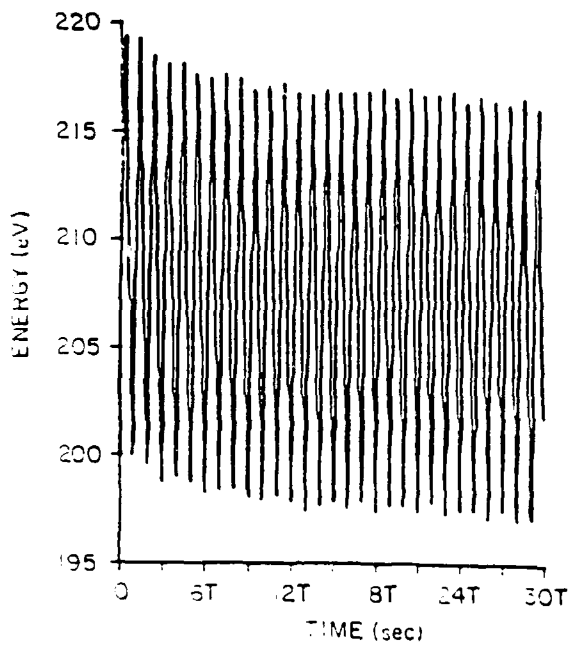

Fig. 13 Perpendicular component of the energy versus time for $\delta = 0.1$, $v_c T = 0.1$, $E_0 = 300$ eV, and a triangular perturbation.

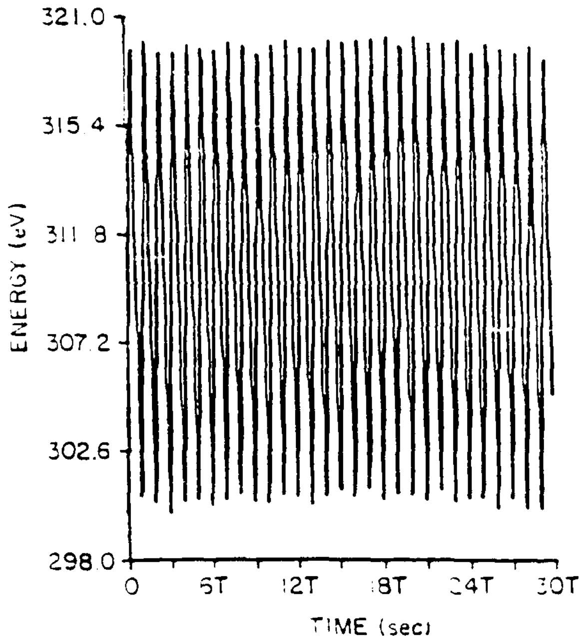

Fig. 14 Total energy versus time for $\delta = 0.1$, $\nu T = 0.1$, $E_i = 300$ eV, and a triangular perturbation.

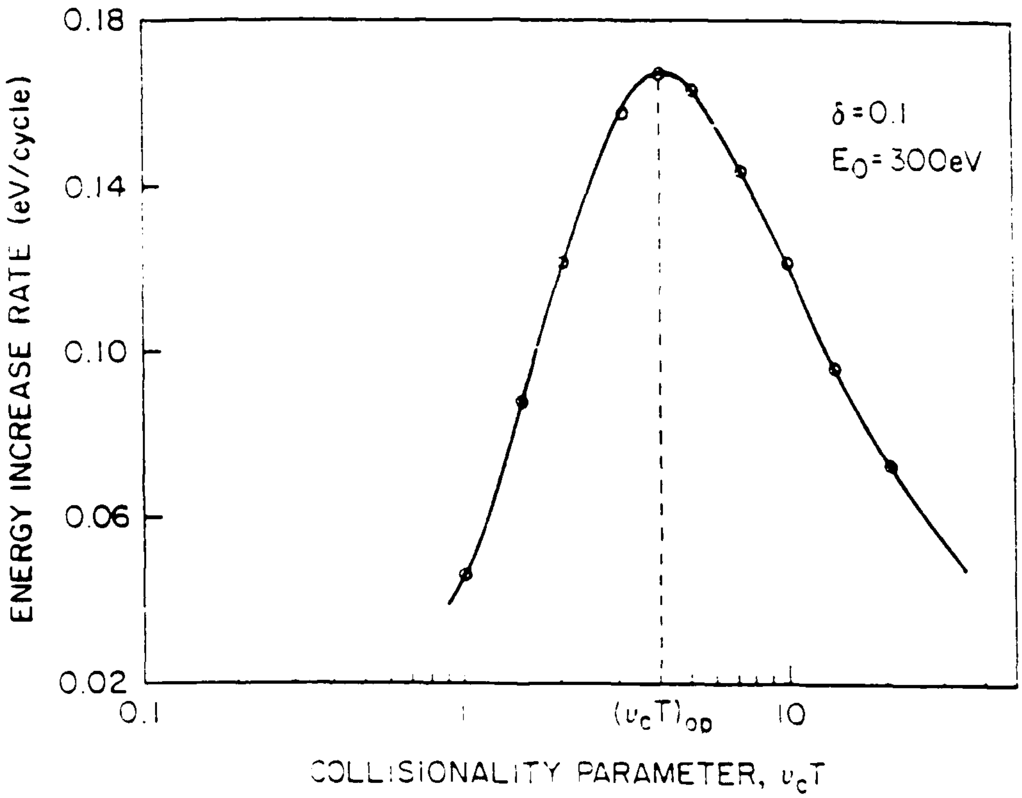

Fig. 15 Energy increase rate versus collisionality parameter for $\delta = 0.1$, $E_0 = 300$ eV, and a triangular perturbation.

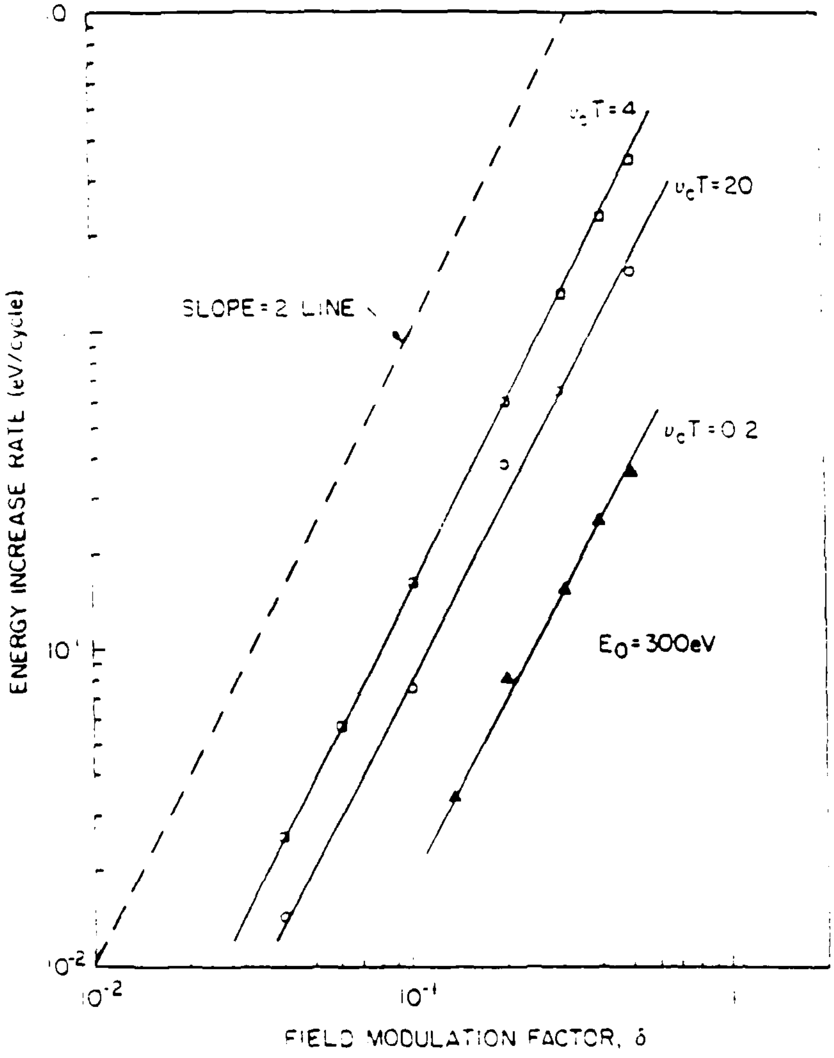

Fig. 16 Energy i crease rate versus field modulation factor for E = 300 eV, several collisionality parameters, and a triangular perturbation.

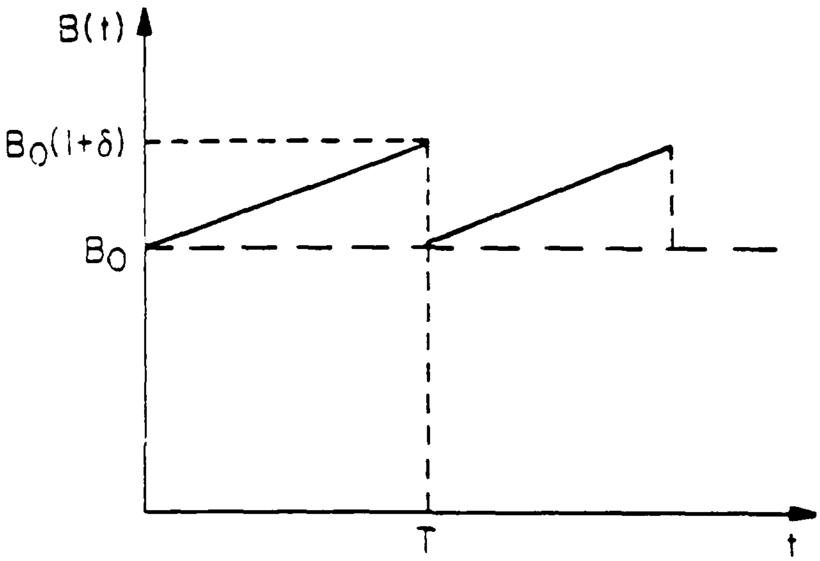

Fig. 17 Magnetic field waveform for a sawtooth perturbation.

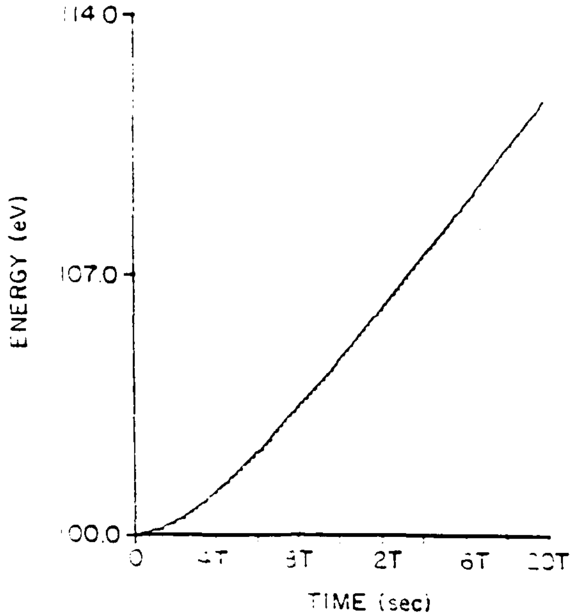

Fig. 18 Parallel component of the energy versus time for $\delta = 0.01$, $v_c T = 0.2$, Eo = 300 eV, and a sawtooth perturbation.

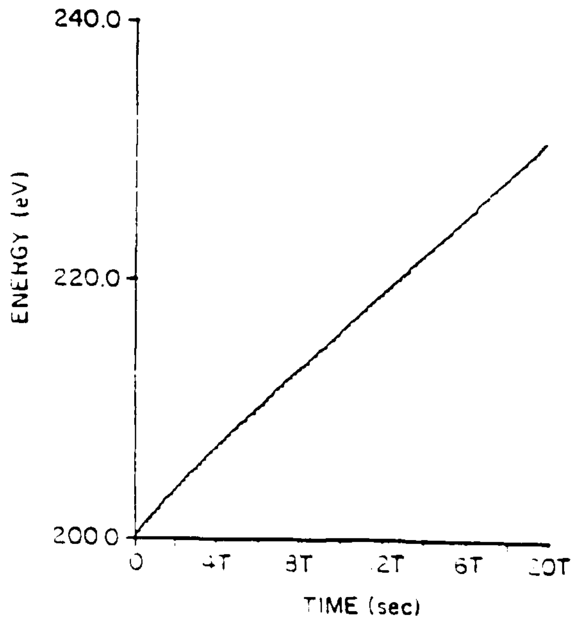

Fig. 19 Perpendicular component of the energy versus time for $\delta = 0.01$, $v_c T = 0.2$, $E_o = 300$ eV, and a sawtooth perturbation.

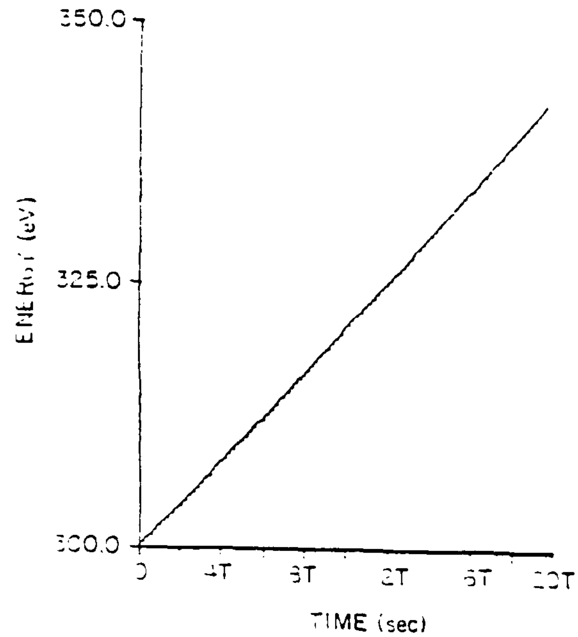

Fig. 20 Total energy versus time for $\delta = 0.01$, $v_c T = 0.2$, $E_0 = 300$ eV, and a sawtooth perturbation.

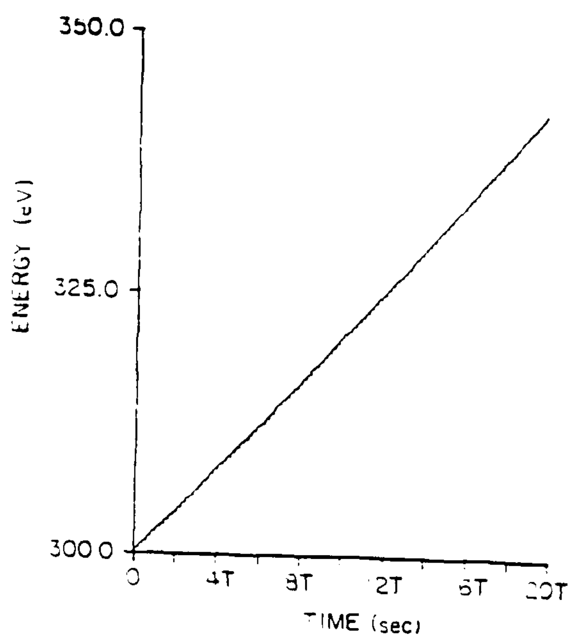

Fig. 21 Total energy versus time for $\delta = 0.01$, $v_c T = 6$, $E_0 = 300$ eV, and a sawtooth perturbation.

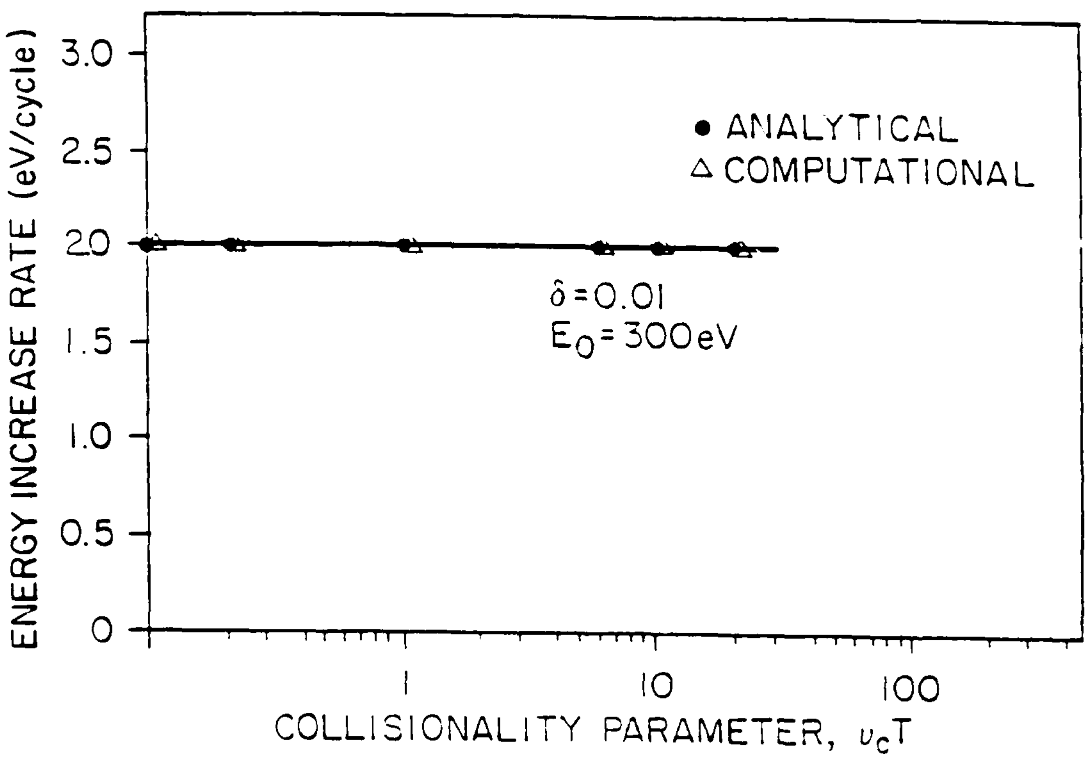

Fig. 22 Energy increase rate versus collisionality parameter for $\delta = 0.01$, $E_0 = 300$ eV, and a sawtooth perturbation.

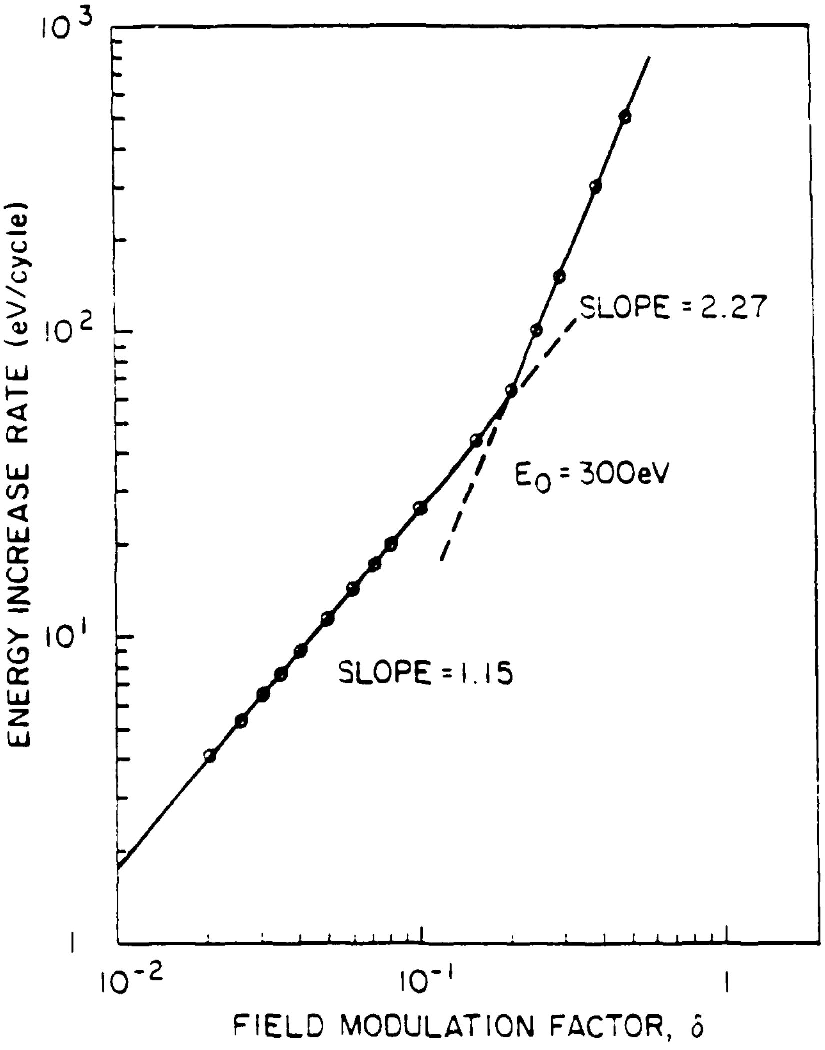

Fig. 23 Energy increase rate versus field modulation factor for E_0 = 300 eV and a sawtooth perturbation.

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Experimental Implementation of Plasma Heating by Collisional Magnetic Pumping

M. Laroussi, Member, IEEE, and J. Reece Roth, Fellow, IEEE

Department of Electrical and Computer Engineering
The University of Tennessee, Knoxville
Knoxville, Tennessee 37996-2100

Abstract

Experimental results from the successful application of collisional magnetic pumping to heat a cylindrical, steady-state helium plasma are reported, for the particular case in which the magnetic field perturbation is a periodic sawtooth function. This sawtooth waveform is necessary in order to effect the nonequilibrium change in energy partition which produces plasma heating proportional to the magnetic field perturbation, ΔB/B. A circuit is described which allows the generation of a sawtooth current through an exciter coil wrapped around the plasma volume, at frequencies up to 200 kHz. Experimental plasma heating data collected using this circuit is compared to theoretical predictions. The predicted direct proportionality of electron temperature increase to excitation frequency has been observed. The electron temperature increase is the same order of magnitude as that predicted theoretically for heating with a sawtooth waveform, but is about four orders of magnitude larger than would be second-order collisional magnetic pumping effected with a sinusoidal magnetic perturbation.

SUBMITTED FOR PUBLICATION

I. Introduction

Magnetic pumping is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_o(1+\delta f(t))$, where B_o is the axial uniform steady state background magnetic field, δ is the field modulation factor defined as $\delta = \Delta B/B_o$, and f(t) is a periodic function of time. When the exciter coil is energized, a magnetosonic wave traveling across B_o at the Alfven speed is launched. This causes a cyclical compression and relaxation of the plasma column.

Four characteristic times play a role in how the plasma is heated. These are the gyration period τ_{cy}, the collision time τ_c, the period of the oscillating field τ_f, and the confinement time of the particles in the heating region τ_{tr}. In collisional heating, these times are related to each other in the following fashion:

$$\tau_{cy} << \tau_c \sim \tau_f << \tau_{tr}.$$

Theoretical treatments giving the energy increase rate have been published[1-7]. In the case where the perturbation function, f(t), is a sinewave, the energy increase rate has been found to be dependent on the second power of the field modulation factor δ and on the particle collision frequency in the plasma [2,3,7]. If the perturbation function is a sawtooth waveform, an energy increase rate is obtained which is proportional to the driving frequency, to the first power of the field modulation factor, δ, and is independent of the particle collision frequency [7-10]. This heating rate is several orders of magnitude larger than the sinusoidal case. In the present series of experiments, the heating effect depends on a nonequilibrium change

in the partition of energy between $E_\perp$ and $E_\parallel$ during the rapid drop at the trailing edge of the sawtooth magnetic perturbation [8,10].

The characteristics of this plasma have been measured and reported elsewhere [Ref. 10, Appendices D, E, F]. In this plasma, the characteristic times discussed above are the following, under "standard" conditions. For a "standard" magnetic field of B_0 = 0.2 tesla, the gyration times are 0.18 nanoseconds for electrons, and 82 nanoseconds for helium ions. The driving frequency varied between 40 and 200 kHz, giving a period for the field perturbation which ranged from 5 to 25 microseconds. The electron-electron collision frequency was only 1.9 kHz in view of the low plasma density, about 1-2 x $10^{15}/m^3$ or lower. The dominant binary collisional process in this plasma is that between electrons and neutrals (neutral densities about n_0 = 3 x $10^{18}/m^3$), with a collision frequency of 265 kHz. It has been shown that, in this plasma, the electron momentum transfer is dominated by electron scattering off of turbulent fluctuating electric fields, yielding an effective collision frequency which we measure by a technique based on broadening of the electron cyclotron resonance peak [11]. For our "standard" plasma conditions, this effective electron collision frequency was approximately 7.5 MHz, giving an effective collision time of 0.13 microseconds. As for the ion collison frequency, the fastest binary process affecting the ion population was ion-neutral collisions, with a collision frequency of 27 kHz and a collision time of 37 microseconds. It is not known to what extent plasma turbulence increases the ion collision rate in this plasma.

The confinement time of electrons and singly-charged helium ions in the plasma are equal, as a result of quasi-neutrality. This particle confinement

time is given by the total charge of one sign in the plasma ($Q = en_e V_p$) divided by the anode current (I_A). For our standard conditions, the electron number density is $n_e = 1.5 \times 10^{15}/m^3$; the plasma volume is 5 liters, $V_p = 5 \times 10^{-3}\ m^3$; and the anode current is 40 milliamps, $I_A = 0.04$ amperes. This gives an average particle confinement time of 30 microseconds. Thus, the characteristic electron times in this experiment, are, in microseconds,

$$0.00018 << 0.13 \sim 5-25 << 30$$

and for ions,

$$0.0082 << 37 \sim 5-25 << 30.$$

Thus, collisional magnetic pumping should occur in this plasma, with a possible question about the ion population, where the (collisionless) ions may be lost in about the same time that it takes them to collide by ion-neutral collison. If the ions have an enhanced collision frequency due to plasma turbulence, the characteristic times for the ion population should also satisfy the inequalities discussed above.

This paper reports experimental heating data collected using a cylindrical steady state plasma generated by a classical Penning discharge [12] when a sawtooth magnetic field perturbation is used. The classical Penning discharge consists of a cylindrical electrostatic trap for electrons, with a positive anode ring at the center and grounded, cold cathodes at the ends. The electrons are confined radially by an axial magnetic field, and reflect back and forth along the axis until they collide with and ionize neutral gas, thus maintaining the discharge. The required sawtooth waveform of the magnetic perturbation is provided by a specially designed state-of-the-art switching circuit using TMOS (Metal-Oxide-Semiconductor) transistors as switches. This circuit allows the generation of a sawtooth-shaped current

through the exciter coil, which in turn generates a magnetic sawtooth perturbation superimposed on the confining magnetic field.

II. Design, Implementation, and Testing of the MOS Switching Circuit

The principle behind generating a sawtooth-shaped current through an inductor is taken from the nature of the relationship between the current and voltage across it,

$$V = L\frac{dI}{dt} \qquad (1)$$

Integrating (1) and solving for the current we get

$$I(t) = \frac{1}{L}\int_{-\infty}^{t} V(t)dt. \qquad (2)$$

If $V(t) = V_0$ is a constant, Equation (2) can be written as

$$I(t) = \frac{V_0}{L}t + I_0 \qquad (3)$$

where I_0 is the initial value of the current, and V_0 is a constant. An obvious approach to produce a linear current-time relationship would be to connect an inductor across an ideal DC voltage source. This is shown in Fig. 1.

If the switch S opens, the current through the inductor would vanish, and a sawtooth shaped current would be generated if the switch S would periodically open and close. The only difficulty is that a current through an inductor cannot vanish instantaneously without inducing high transient voltages that would damage the switch (this is also due to the nature of the current-voltage relationship for an inductor). The solution to the above problem is simple and consists of offering a path other than the switch, through which the current can flow and damp out. Fig. 2 shows such a circuit.

Let us assume that the switch is closed from $t = 0$ to $t = t_0$ and open from $t = t_0$ to $t = t_1$. Then, the current through the inductor satisfies the following equations,

$$I_L(t) = \frac{V_0}{L} t + I_0 \qquad 0 \leq t \leq t_0, \tag{4}$$

and

$$I_L(t) = \left(I(t_0) - \frac{V_0}{R} \right) e^{-\frac{R}{L}(t - t_0)} + \frac{V_0}{R} \qquad t_0 \leq t \leq t_1. \tag{5}$$

Fig. 3 is a schematic drawing of the switch control voltage and the respective current waveform. To approach a sawtooth waveform the following condition has to be satisfied

$$\frac{L}{R} < (T - t_R) << t_R \tag{6}$$

To accomplish a sawtooth perturbation superimposed on the background magnetic field, a circuit equivalent to Fig. 2 has been designed, constructed, and tested. The inductor is the exciter coil, the constant voltage source is a Lambda DC regulated power supply, and the switch is a Motorola TMOS 2N6770 transistor. The selection of this transistor is based on its high voltage standoff (500 V), low series on resistance (0.4 Ω), high switching speed (80 ns turn-on time and 220 ns turn-off time), and high current capabilities (25 A in pulsed mode). Because each of these devices has a positive temperature coefficient for current, a parallel arrangement of them tends to share currents in a balanced fashion. This is advantageous if high current levels are used.

Fig. 4 is a schematic diagram of the circuit actually used to generate the sawtooth-shaped current through the exciter coil. This circuit consists of two parts, the switching arm and the driving stage. The switching arm consists of the DC power source, the exciter coil, the switch (transistor T_1), and the

damping resistor R. It is through this arm that the current ramps up and damps out periodically. The driving stage is the part of the circuit which provides the periodic nature of the current waveform, its frequency, and its amplitude.

The operation of the driving stage is quite simple. It consists of a control signal fed into a current buffer which drives two complementary MOS switches. When the control signal is low, transistor T_2 (MTP 8P10) is on and transistor T_3 (IRF 510) is off. This automatically puts 10 volts between the gate and the source of transistor T_1, consequently turning it on. Fig. 5 illustrates the state of each transistor during this regime. As soon as T_1 turns on, the current starts ramping up through the inductor until the control voltage changes state, at which time the current reaches its maximum value. As the control voltage goes high, T_2 turns off, T_3 turns on, consequently grounding the gate of T_1 and turning it off. At this time, the current stops flowing through the transistor and starts flowing through the damping resistor R. Fig. 6 illustrates the state of each transistor during this regime.

Transistors T_2 and T_3 work on an on-off basis. They are needed to allow the input capacitance of T_1 (3000pF) to charge up and discharge through a very low resistance (0.5 Ω). This is essential if high speed switching is to be achieved. The current buffer (CD4050) is introduced between the control signal and the gates of T_2 and T_3 to help provide sufficient current at the switching times.

The maximum value of the current is determined by the duty cycle of the control signal and magnitude of the DC voltage delivered by the power source. The minimum time alloted for the current to damp out is determined by the

sum of the response times of all the devices involved. This sets a limit on the maximum value of the duty cycle, and consequently on the maximum value of the time constant L/R. This time should be at least 3 times smaller than the time during which transistor T_1 is off. This condition, along with the maximum voltage restriction across T_1, permits the selection of resistor R. Currents up to 25 amperes and driving frequencies up to 200 kilohertz have been achieved.

III. Operation of the Plasma Heating Circuit

To achieve first order heating, a sawtooth perturbation is superimposed on the background magnetic field that confines a cylindrical column of plasma 10 cm in diameter and 64 cm in length [10]. This is done by using the switching circuit shown in Fig. 4. The DC source used is capable of delivering up to 80 A. The selected voltage is 5 V. The damping resistor, R, is chosen to be 25 Ω. The exciter coil is a single-layer cylindrical solenoid 50 cm long, 6.26 cm in radius, and has 8 turns. Its inductance is 2 μH. A Faraday shield is present between the coil and the plasma, to eliminate the effects of high electrostatic driving potentials on the coil, on the plasma characteristics. The total inductance of the circuit, including the inductance of the exciter coil and of all the leads, amounts to 6 μH. The response time of the circuit during the "on" regime is 365 ns and during the "off" regime is 620 ns. For proper operation, the current ramp-up time should be many times larger than the turn-on time. The time alloted for the current to decrease to a small value should be larger than the time constant, L/R, which is about 200 ns. The above considerations require that an operating frequency less than a few

hundred kilohertz be used if any substantial perturbation is to be applied. This is good performance, considering that currents of many amperes are switched on and off in a few microseconds through an inductor. Fig. 7 and Fig. 8 show the control signal and current waveforms achieved at various operating frequencies.

The power generated by the switching circuit can be calculated as follows. During the current ramp-up time, between $t = 0$ and $t = t_0$, the voltage across the exciter coil is constant and equal to V_0, and the current is given by

$$i(t) = \frac{V_0}{L} t \qquad 0 \le t \le t_0 \tag{7}$$

The energy stored in the inductor during this period is

$$W = \int_0^{t_0} V(t)\, i(t)\, dt. \tag{8}$$

Substituting the expresions of V(t) and i(t) in Equation (8) yields

$$W = \int_0^{t_0} \frac{V_0^2}{L} t\, dt, \tag{9}$$

which gives

$$W = \frac{V_0^2}{2L} t_0^2. \tag{10}$$

The power is given by

$$P = \frac{W}{t_0} = \frac{V_0^2}{2L} t_0 \tag{11}$$

The power stored in the inductor is then damped in resistor R between $t = t_0$ and $t = T$. This can be checked as follows. The energy damped in resistor R is given by

$$W = \int_0^{T} V_R(t)\, i_R(t)\, dt. \tag{12}$$

where $V_R(t)$ and $i_R(t)$ are given by

$$V_R(t) = 0 \qquad 0 \le t < t_0,$$
$$V_R(t) = \left(\frac{RV_0}{L} t_0 - E \right) e^{-\frac{R}{L}(t - t_0)} + V_0 \quad t_0 \le t \le T, \tag{13}$$

and

$$i_R(t) = 0 \qquad 0 \le t < t_0,$$
$$i_R(t) = \left(\frac{V_0}{L} t_0 - \frac{V_0}{R} \right) e^{-\frac{R}{L}(t - t_0)} + \frac{V_0}{R} \quad t_0 \le t \le T. \tag{14}$$

Substituting into Equation (12) and assuming that $T - t_0 >> L/R$ gives

$$W \approx \frac{V_0^2}{2L} t_0^2 + \frac{V_0^2}{R} T - \frac{3}{2} \frac{V_0^2}{R^2} L. \tag{15}$$

The power is given by

$$P = \frac{W}{T} \approx \frac{V_0^2}{2L} t_0 + \frac{V_0^2}{R} - \frac{3}{2} \frac{V_0^2}{R^2} \frac{L}{T}, \tag{16}$$

but since $T >> L/R$, Equation (16) can be written as

$$P \approx \frac{V_0^2}{2L} t_0 + \frac{V_0^2}{R} \tag{17}$$

This is in agreement with Equation (11). At an operating frequency of 100 kHz, a maximum power of about 48 watts is generated by the RF circuit. This RF power is comparable to the DC power needed to run the Penning discharge to which collisional magnetic pumping is applied.

IV. Experimental Plasma Heating Data

The diagnostic instruments used to observe changes in the plasma characteristics are a Langmuir probe and a retarding potential energy analyser. The power absorption is checked by monitoring the change in the

RF power as compared to the change of the discharge power when collisional magnetic pumping is turned on.

Power coupling between the RF wave and the plasma has been successfully achieved. This has been observed by monitoring the discharge DC power along with the RF power. The change in the DC power is observed by noting the decrease in the discharge current when the RF circuit is turned on. The change in the RF power is observed by noting the change of the power dissipated in resistor R. This is easily calculated from the voltage decrease across R. Fig.9a and Fig. 9b show the current and the voltage waveforms across R when the plasma is off and when the plasma is on. Fig. 9c and Fig. 9d are 10 times magnifications of the peak of the voltage across R. It shows that when the plasma is on, a decrease of 10 volts occurs. Both power changes are found to be comparable in magnitude and are between 10 and 20 percent of their respective nominal values. They also show the same functional dependence on the operating parameters, such as the RF driving frequency and the plasma density. Fig. 10 shows a plot of the changes in the RF power and the DC power versus the operating frequency.

A theoretical analysis of collisional magnetic pumping with a sinusoidal waveform for the magnetic field [2,3,7-10] predicts a heating rate

$$\frac{dE}{dt} = \frac{\delta^2 E_o}{6} \frac{\omega^2 v_c}{\frac{9}{4} v_c^2 + \omega^2} \quad \mathrm{eV/sec} \tag{18}$$

where E_0 is the initial electron energy, ω is the coil driving frequency in radians/second, and v_c is the effective collision frequency in Hertz. This heating rate is proportional to the square of the field modulation factor, δ, a small quantity. Computational investigation of the heating rate with a

symmetric triangular waveform [10] shows that such a waveform results in a heating rate about 1/6 that of Eq. 18, presumably because the perpendicular energy of the particles spends less time near its maximum value with this waveform.

If a sawtooth perturbing waveform is used, with a nonequilibrium change in energy partition at the trailing edge of the waveform, it can be shown theoretically [7-10] that the heating rate is linearly proportional to the field modulation factor and to the coil driving frequency,

$$\frac{dE}{dt} = \frac{\delta\omega}{3\pi} E_0 \quad \text{eV/sec} \tag{19}$$

Thus, the linear proportionality of the power absorbed by the plasma with frequency which is demonstrated in Figure 10 is an important result, since it is consistent with the functional dependence predicted in Eq. 19.

An increase in the RF driving frequency, ω, has a two-fold effect: an increase in power absorption and an increase in the plasma heating rate. Figs. 11 and 12 show that such an increase of the electron kinetic temperature occurs. Within experimental error, this temperature increase is directly proportional (slope $S = 1.0$) to the amount of absorbed power (Fig. 11) and to the driving frequency (Fig. 12). These dependences are as predicted by Eq. 19. In Figures 11 and 12, the error decreases with increasing ΔT_e because the errors in reducing the Langmuir probe data tend to be constant, and this becomes a smaller proportion of T_e as the electron temperature increases.

The technical difficulties of generating the sawtoothed magnetic perturbation limited us to no more than a few tens of watts of power input to the plasma in these experiments. This limitation prevented us from varying the field modulation factor, δ, over a wide enough range to test for the linear

dependence on it predicted by Eq. 19; we were forced to operate at the highest achievable value of δ to avoid having the heating effect lost in the errors occasioned by reducing the Langmuir probe data. We presently are planning further experiments with a kilowatt power input capability. This should not only allow us to sustain the plasma with collisional magnetic pumping alone, but also to demonstrate the linear dependence of heating rate on the field modulation factor.

The heating data shown in Figure 12 are order-of-magnitude consistent with the first order heating predicted by Eq. 19. The data shown in Figure 12 were taken for a field modulation factor of $\delta = 0.005$; a driving RF frequency which ranged from 40 to 150 kHz; an electron kinetic temperature of $E_0 = 10$ eV; an effective electron collision frequency of approximately $v_c = 7.5$ MHz; and a global particle containment time of $\tau_c \approx 10^{-4}$ seconds. The energy increase predicted by Eq. 18 for a sinusoidal waveform under these conditions is only about 10^{-4} eV; far too little to be observed. Equation 19 predicts for the sawtooth waveform an energy increase of $\Delta E \approx 0.33$ eV. This is order of magnitude consistent with the energy increase of $\Delta E = 2 \pm 0.5$ eV actually observed. The fact that more heating was observed than predicted for the sawtooth waveform may be due to fine-scale features of the actual waveforms shown on Figs. 7 and 8, or, more likely, that the electrons in the core of the plasma (where T_e and n_e were measured) had a containment time longer than the global average of 100 microseconds, by this factor.

The ion energy distribution does not undergo a significant change. This is consistent with the fact that the ion dwell time under the heating region is essentially collisionless. Fig. 13 shows that the energy distribution of the ions

as monitored by a retarding potential energy analyser does not change substantially when magnetic pumping is turned on.

V. Conclusion

A magnetic field sawtooth waveform generator has been successfully developed to provide powers up to 50 watts at frequencies up to 200 kHz. Electron heating has been experimentally observed. Its functional dependence on driving frequency and its magnitude were consistent with the theoretical prediction of Equation (19). The absolute measured value of the electron kinetic temperature increase was approximately a factor of 6 larger than predicted for heating with a sawtooth waveform. This order of magnitude agreement probably was no better because the electron containment time in the plasma core, where ΔE was measured, was longer than the global value calculated from the total charge in the plasma and the anode current. The energy increase due to magnetic pumping with a sinusoidal waveform, for our experimental conditions, would have been only about 10^{-4} eV.

Acknowledgement

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Figure Captions

Fig. 1. Ideal DC voltage source driving an inductor.

Fig. 2. Ideal DC voltage source driving an inductor with a damping resistor.

Fig. 3. a) Switch control voltage; b) Current waveform.

Fig. 4. Circuit generating a periodic current sawtooth through the exciter coil.

Fig. 5. State of the transistors when the switch is on.

Fig. 6. State of the transistors when the switch is off.

Fig. 7. a) Scope trace of the control signal with 5 μs/division on the horizontal axis (f = 75 KHz) and 5 volts/division on the vertical axis; b) Current trace with 5 μs/division horizontally and 4 amperes/divison vertically; c) Gate voltage trace with 5 μs/division horizontally and 5 volts/division vertically.

Fig. 8. a) Scope trace of the control signal with 20 μs/division on the horizontal axis (f = 40 kHz) and 5 volts/division on the vertical axis; b) Current trace with 20 μs/division horizontally and 5 amperes/division vertically; c) Gate voltage trace with 20 μs/division horizontally and 5 volts/division vertically.

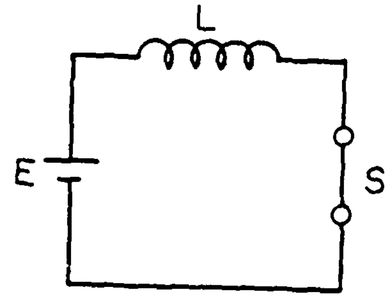
Fig. 9. Scope trace of inductor current and resistor voltage (f = 100 kHz) when a) Plasma is off; b) Plasma is on; c) Peak of resistor voltage, with 5 μs/division horizontally and 5 volts/division vertically, when plasma is off; d) When plasma is on.

Fig. 10. DC and RF power decrease versus driving frequency. The slope, S, of the straight lines is indicated.

Fig. 11. Electron kinetic temperature increase versus DC plasma input power decrease for a sawtooth perturbation. The slope, S, of the straight line through the data is indicated.

Fig. 12. Electron kinetic temperature increase versus driving frequency for a sawtooth perturbation. The slope, S, of the straight line through the data is indicated.

Fig. 13. Integrated ion energy distribution function (retarding potential energy analyzer trace) with and without magnetic pumping for a DC discharge anode voltage, V_A = 2.2 kV, a discharge anode current I_A = 32 mA, background pressure of helium gas, P = 110 μ Torr, RF driving frequency, f = 100 kHz, and a sawtooth perturbation.



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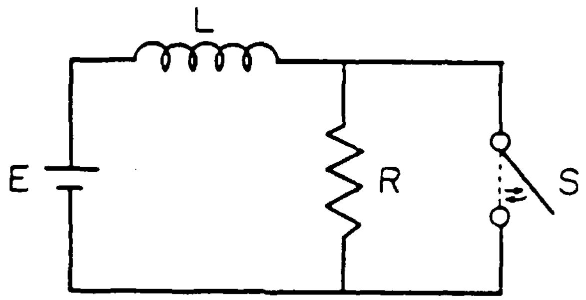

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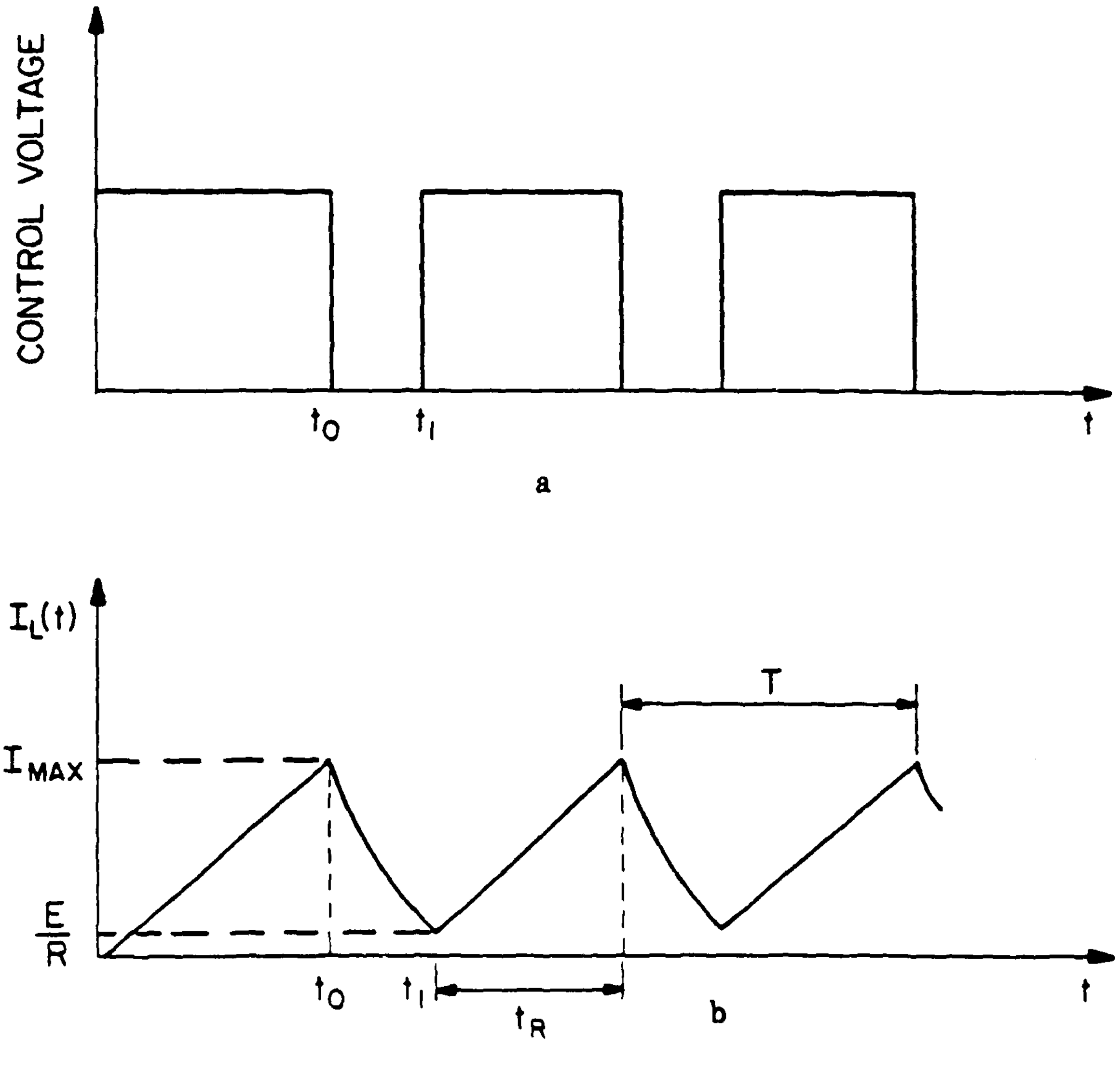

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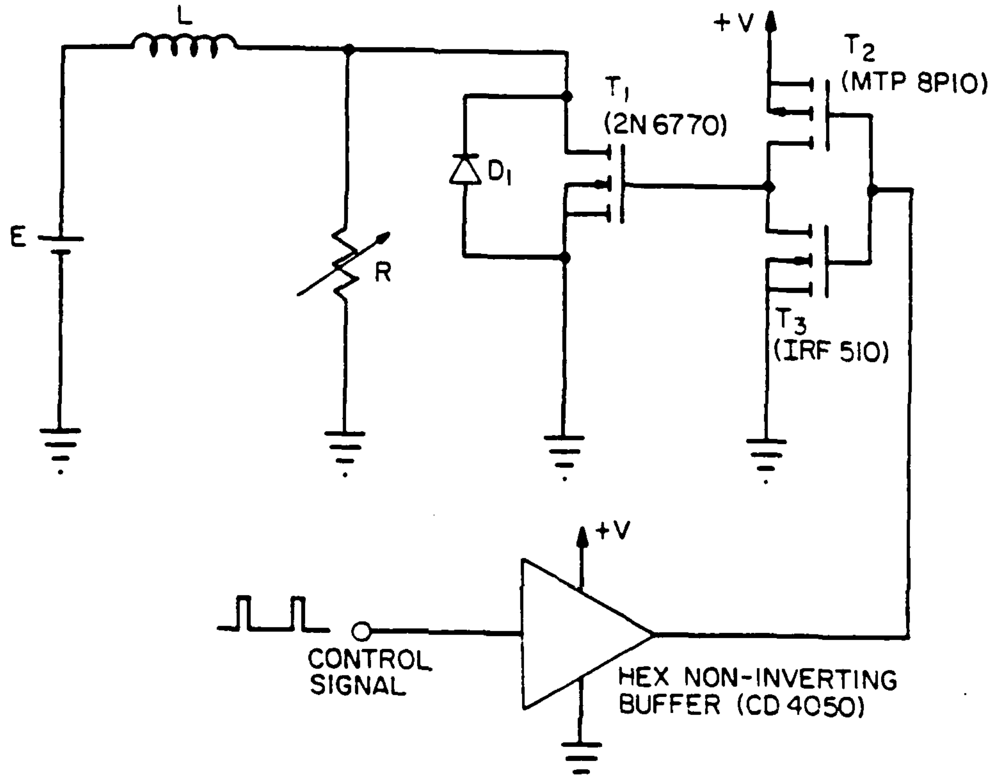
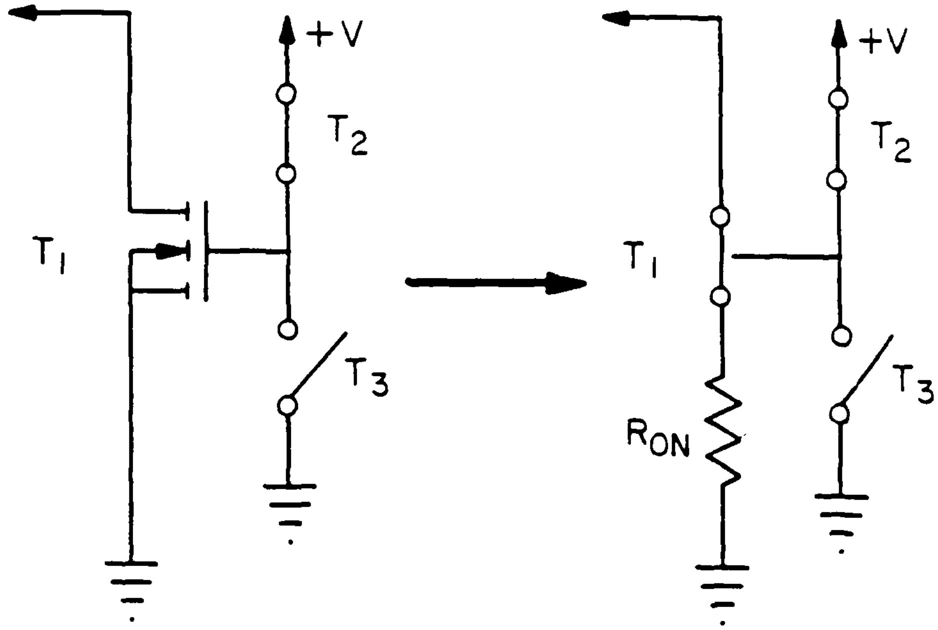


Fig. 4. Circuit generating a periodic current sawtooth through the exciter coil.



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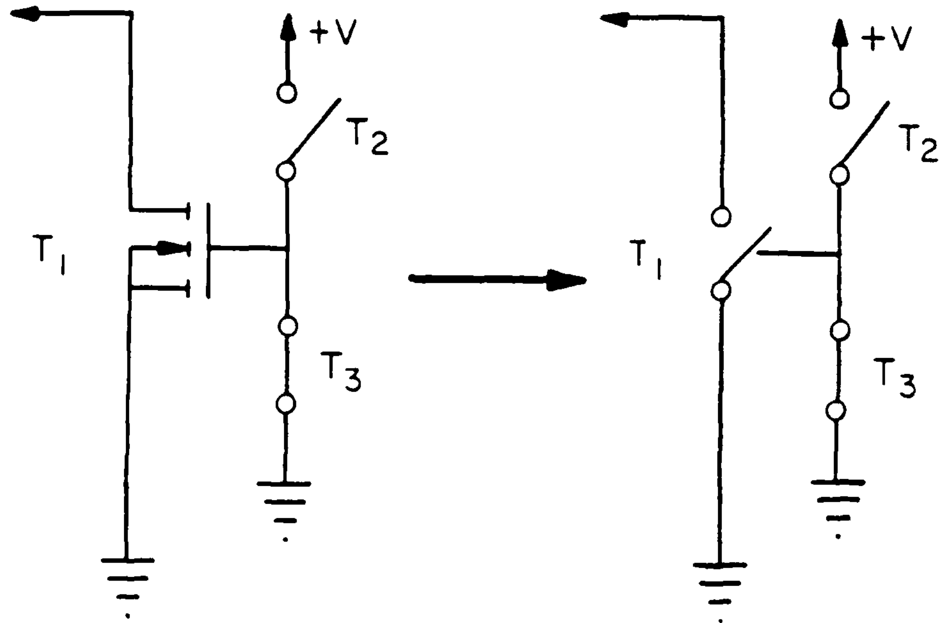

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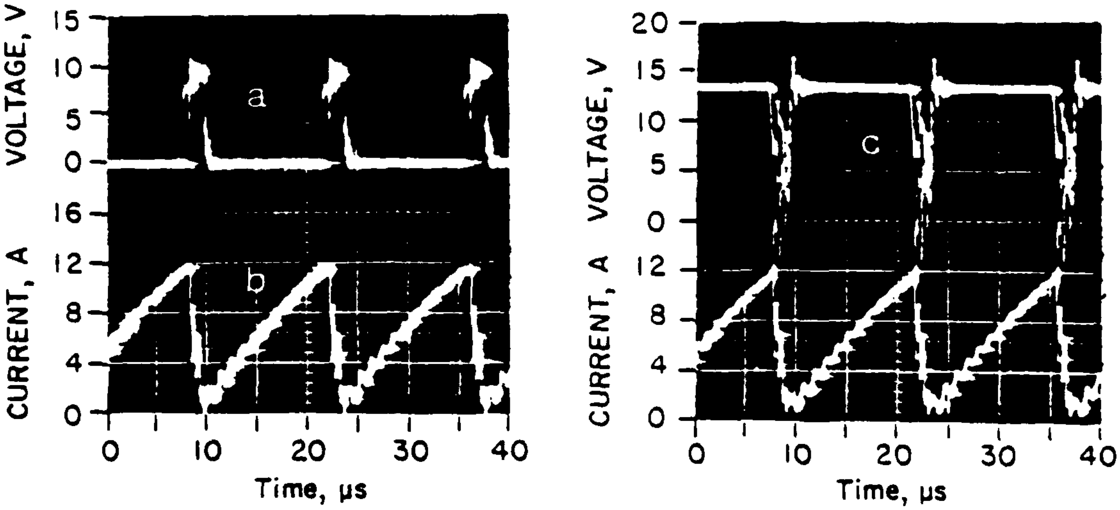

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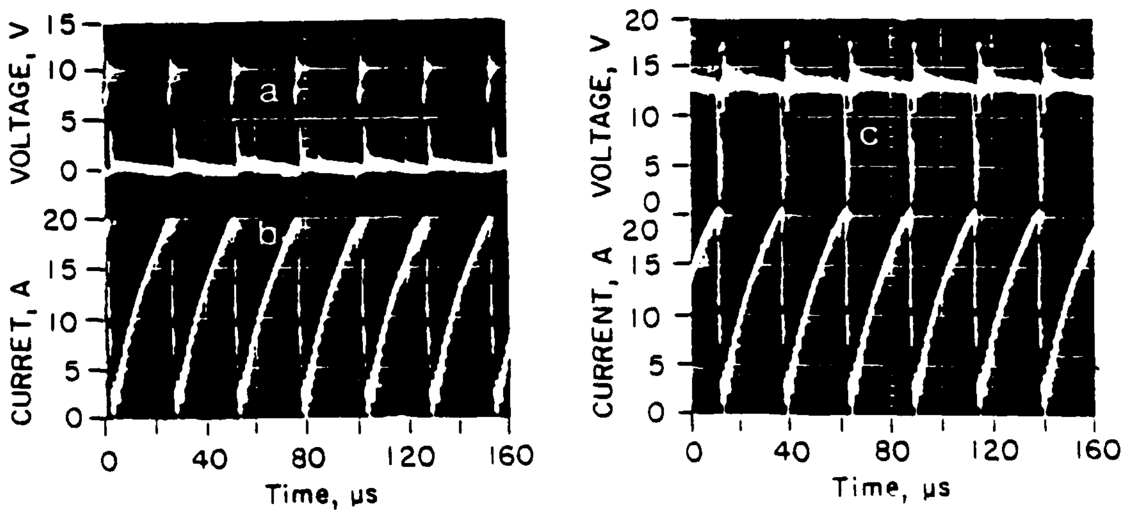

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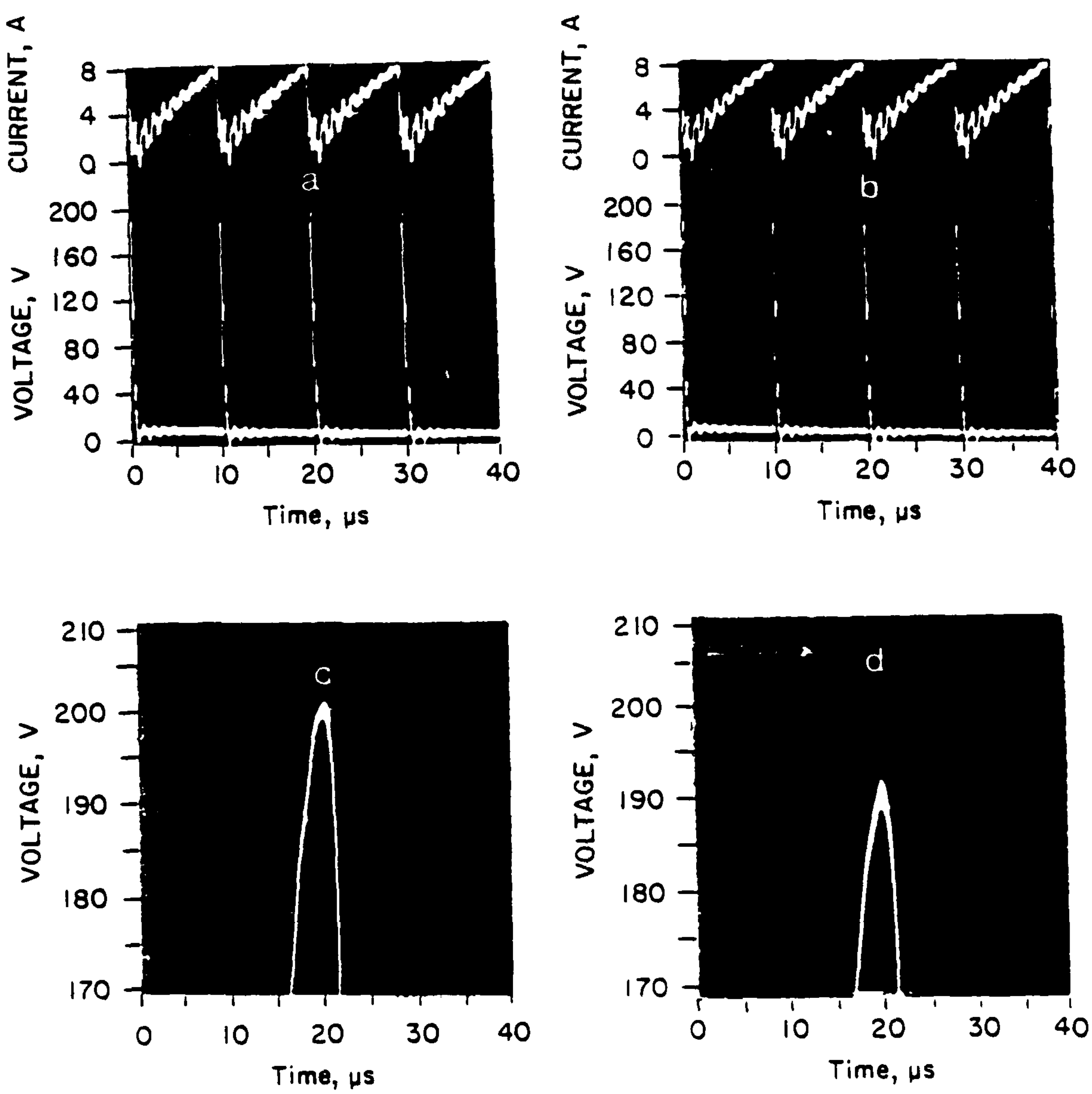

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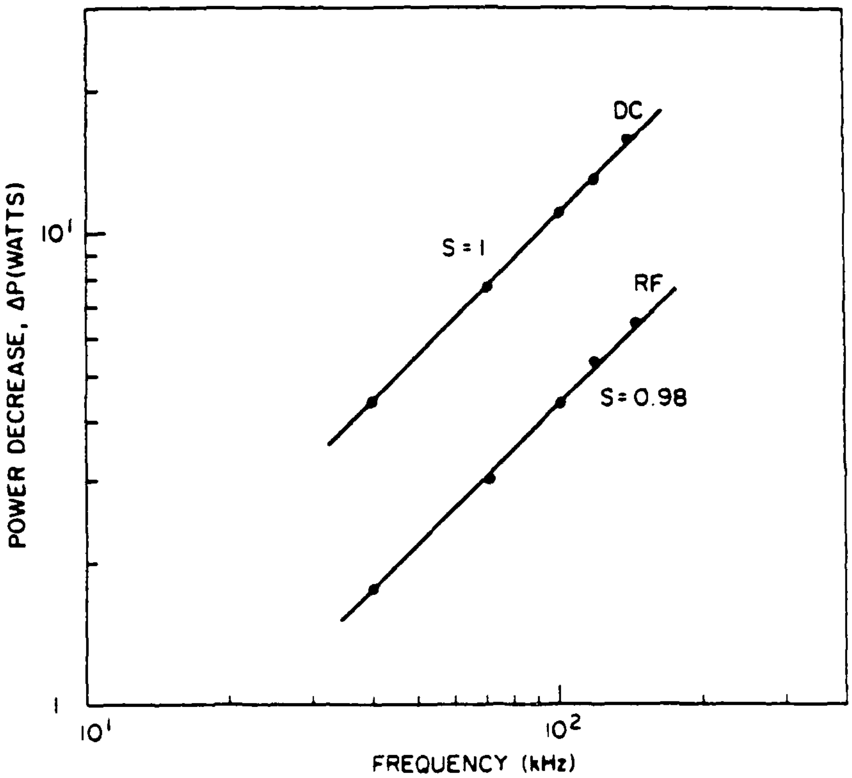

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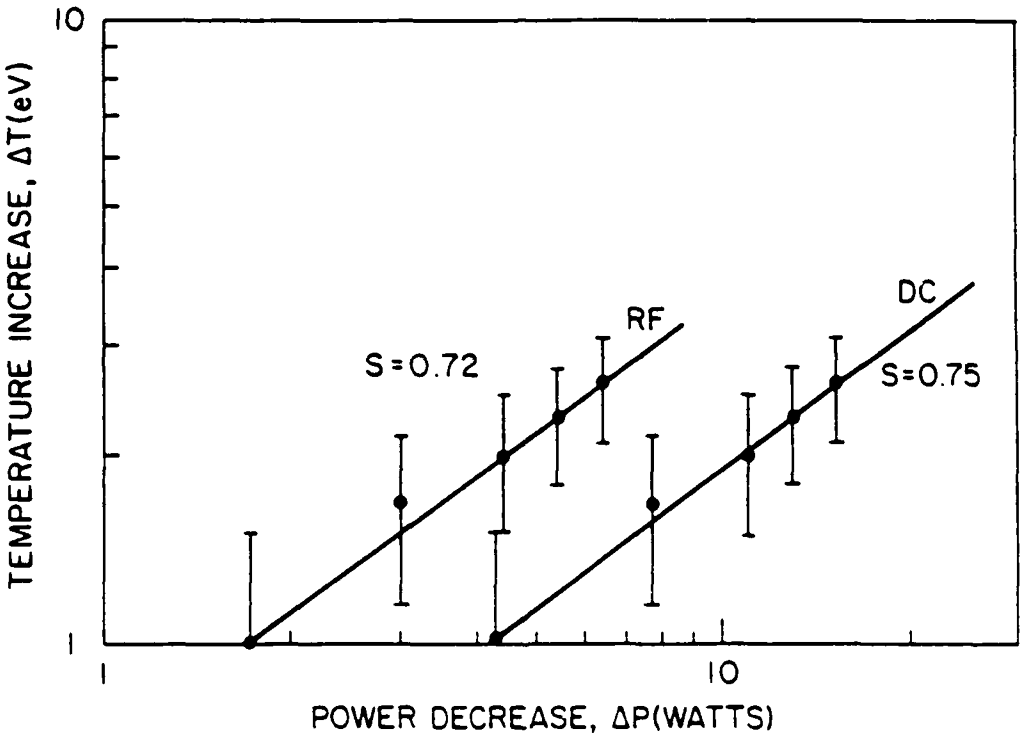

Fig. 11. Electron kintic temperature increase versus power decrease for a sawtooth pertubation. The slope, S, of the straight lines through the data is indicated.

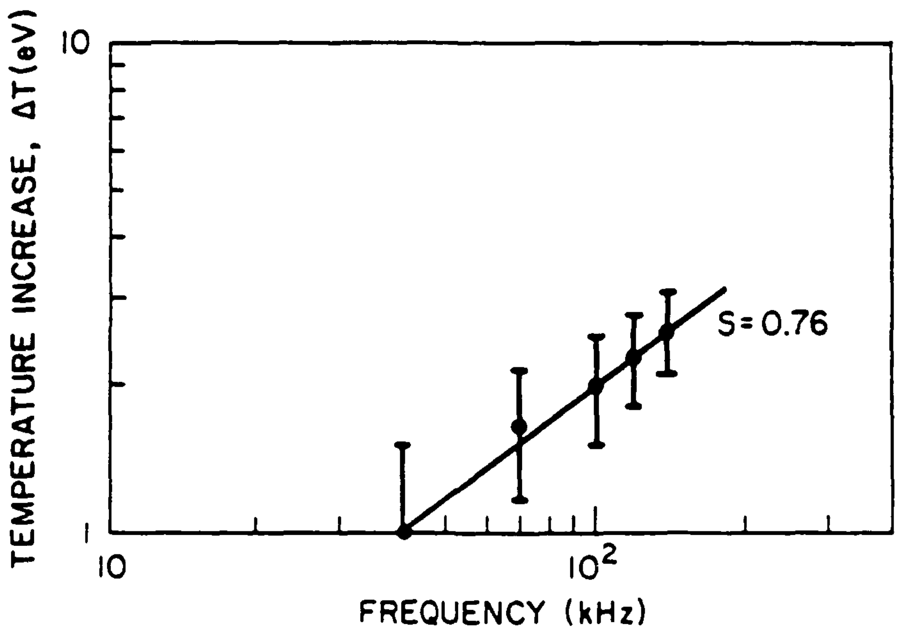

Fig. 12. Electron kinetic temperature increase versus driving frequency for a sawtooth perturbation. The slope, S, of the straight line through the data is indicated.

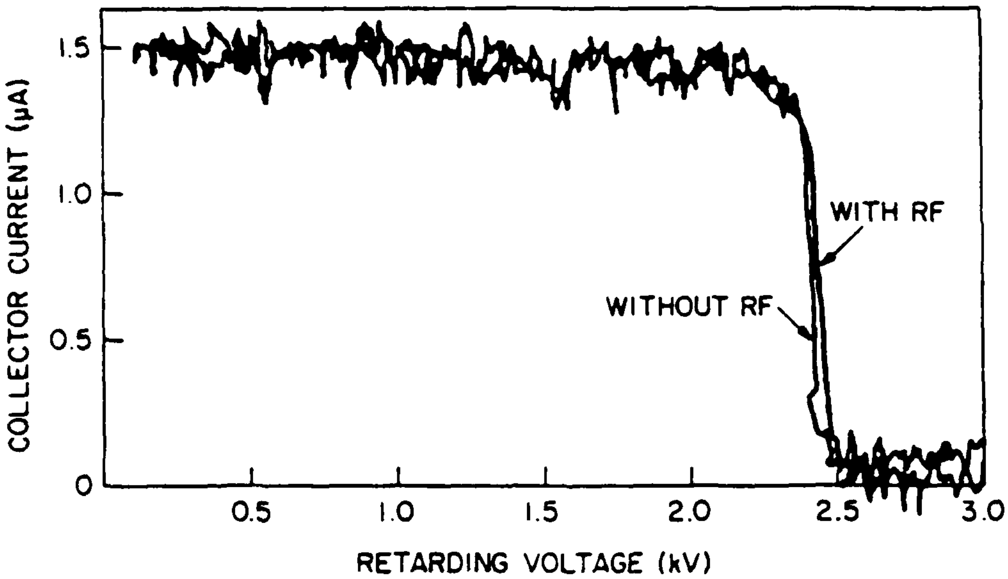

Fig. 13. Ion energy distribution with and without magnetic pumping for $V_A = 2.2$ kV, $I_A = 32$ mA, P = 110 μ Torr, f = 100 kHz, and a sawtooth perturbation.

Recent Developments in the Orbitron MASER*

Igor Alexeff, Mark Rader, and Fred Dyer

University of Tennessee
Knoxville, TN 37996-2100

Abstract

The Orbitron MASER is a device which can be used to produce millimeter and submillimeter radiation. Frequencies up to 1 THz have been observed. It can be operated in a pulsed mode or in a steady state mode, using a hot cathode. In recent experiments we have used the entire outer wall of the device as a hot cathode. We have also been using the device as a fast opening switch.

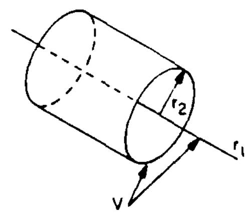

FIGURE 1a

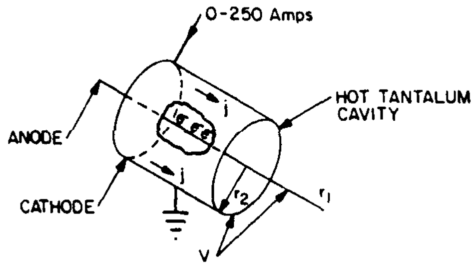

FIGURE 1b

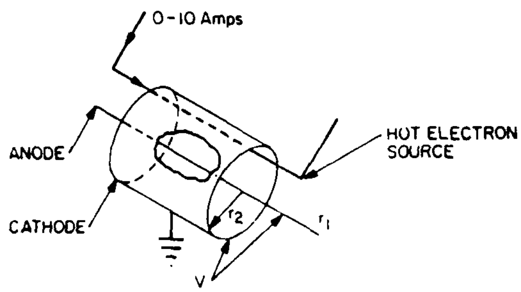

FIGURE 1c

Introduction

The Orbitron MASER is a negative mass unstable device, which can be used to produce millimeter and submillimeter RF radiation. In its basic design, the Orbitron is a coaxial structure with a high positive potential between the outer cathode and inner anode wire, as shown in figure 1a. Electrons are supplied to this system by either a pulsed internal glow discharge or by an oxide coated hot electron emitter. These electrons, due to an initial angular velocity, go into orbit around the positive central wire and emit a frequency that is inversely proportional to the radius of their orbits. Emission, from the pulsed form of this device, has been observed at a frequency of 1 THz.[1]

We have been studying the effects of making other changes to both the geometry of the device and the geometry of the electron emitter. One very interesting change has been the use of a hot oxide coated tantalum cavity, shown in figure 1b, to supply electrons to the device instead of the conventional oxide coated hot axial filament, shown in figure 1c. This change has allowed us to achieve much higher currents in the hot cathode version of this device[2].

The plasma opening switch is a device which can be used to switch open high energy DC circuits where mechanical switches would arc on opening the circuit. The Orbitron MASER can be made into one of these devices by adding end plates to the basic Orbitron coaxial structure, as shown in figure 2. In the "on" condition, these plates are grounded to the cavity and so trap the electrons from a steady state glow discharge in orbit around the central wire. If one of these end plates is raised to a small positive potential, we have found that all of the electrons excape from the system, current flow between the cathode and anode stops, and the glow discharge extinguishes thus opening the switch.[3]

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ary of the Orbitron MASER

. The Orbitron MASER is a coaxial device ch produces radiation by a process know as a ative mass instability. This instability urs in rotating systems such as gyrotrons. occurs when the dynamics of the radiation ducing particles are such that as the ticles lose energy and produce radiation the ular velocity of these particles increases. Orbitron is this type of system.

In the Orbitron MASER, the electrons ich drive the negative mass instability are orn on the inner surface of the cavity. These lectrons are born with a small amount of ransverse energy, and acquire radial energy from the radial electric field. The electrons then go into orbit around the central anode, due to the original transverse energy. The outer cathode forms a microwave cavity resonator. This rotating ring of electrons couples to microwave cavity modes and generates RF radiation. When this occurs, the electrons loose energy and fall into a lower orbit. Due to the equations of motion, the electrons then gain angular velocity.

It is possible to derive the frequency of radiation for the Orbitron by a simple force balance for circular orbits around the central anode wire. If one looks at the centrifugal force on the electron while in orbit, this is

$$F_c = (m\, v^2)/r \qquad (1)$$

where F_c is the outward centrifugal force, m_e is the electron mass, r is the particle radius from the orbital center, and v is the electron velocity. The inward force caused by the logarithmic potential well can be expressed as a function of the applied potential, and is

$$F_e = (eV)/(r\ln(r_2/r_1) \qquad (2)$$

where F_e is the force caused by the electric field, e is the electronic charge, V is the applied potential, r_2 is is the cathode radius, and r_1 is the anode radius.

If we equate equation 1, equation 2, and divide both sides by m and r, we get,

$$(v/r)^2=(eV)/(mr^2\ln(r_2/r_1)) \quad (3)$$

where the first term is the square of angular radian frequency Ω. We can solve equation 3 for this frequency. So that

$$\Omega = r^{-1}((eV)/(m\ln(r_2/r_1))^{1/2} (4)$$

This gives us that the frequency of rotation is inversely proportional to the radius and proportional to the square root of the voltage.[4,5] If one does the case of noncircular orbits[5] one finds the same equation, but it differs by a constant which is dependent on the degree of ellipticity. This is also the frequency of radiation.

If one wants an idea of the highest frequency possible out of the device, one merely has to calculate the frequency of a particle in a grazing orbit around the central anode. So if one wants high frequency, the anode wire must have a very small radius. We have used tungsten wires in our pulsed Orbitron MASER with a diameter of .0075 millimeters or larger. These very fine wires have enabled us to have routine operation at emitted wavelengths of .5 millimeters and we have recorded emissions at .3 millimeters or 1 THz[1].

The Orbitron MASER has two basic advantages over the gyrotron. These advantages being that the gyrotron requires both a strong axial magnetic field and a relativistic electron beam to operate. The relativistic electron beam is required to achieve a negative mass unstable state, which is a natural consequence of the Orbitron geometry.

Hot Cathode Operation of the Orbitron MASER

One of the two variations of the Orbitron MASER, is the Steady State Orbitron.

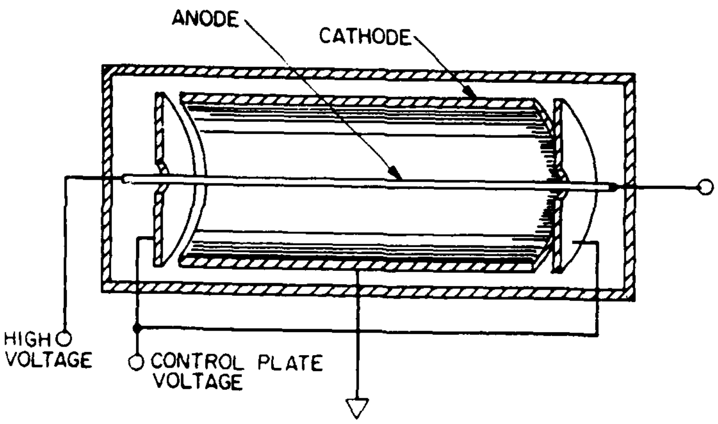

FIGURE 2

new cathode designs in order to increase the current, on a short time basis, to the central anode. This increase in current is to increase the power output and frequency of the device. One of the more interesting variations has been to make the entire outer cathode a hot electron emitter. This device is shown in figure 1b.

We tested the device in a long pulse high current, 2 or 3 amps, mode of operation. The reason for this long pulse mode of operation was to minimize anode heating. During these long pulses, we were able to achieve frequency emissions from this device at frequencies up to approximately 10 GHz The anode wire diameter, for this test, was .125 millimeters, and the outer cathode diameter was 31. 25 millimeters.

Opening Plasma Switching

The Orbitron MASER has other uses than that of a microwave oscillator. It can be used, with minor modifications, as a fast opening plasma switch. This is accomplished by the addition of two end plates to improve end electron confinement.

When the switch is "closed", both end plates are at the cathode potential. This traps electrons, caused by cosmic radiation, in orbit between the cathode and positive anode. These trapped electrons ionize residual gas in the system and create a steady state glow discharge, thus creating a path for current flow between cathode and anode.

The switch is "opened" when one of the plates is switched from the cathode to the anode potential. This spoils the end confinement and causes the electrons to flow axially out of the device. If the pressure is low enough, the ionization process then stops, the glow discharge goes out, and current flow stops. This is demonstrated in figure 3.[3]

During a test of this device, we pulsed the switch to a moderate current level, as shown at the first of figure 3. Then during the middle of this current pulse, we interrupted the current flow by switching one of the plates to the anode potential. This gave a switching time on the order of 5 microseconds. The undershoot is an artifact of the sensing circuit[6].

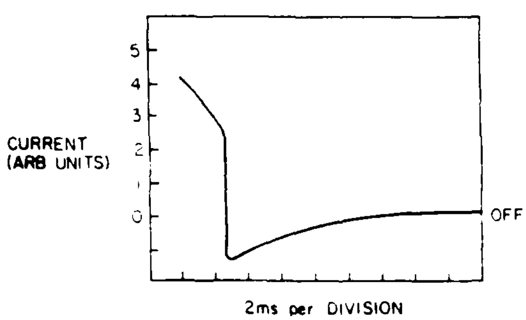

FIGURE 3

In order to get a better idea of the voltage required to switch the device from the closed state to the open state, we also tried imposing different potentials to the end plates to see what percentage of the anode potential was required to switch the device. This was accomplished by using a separate low voltage supply attached to the switching plates. We found that this switching voltage is a function of both the the applied potential across the switch and the background gas pressure, as show in figure 4, but under all test conditions the required voltage was less that 15% of the applied anode potential.[7]

Conclusion

The Orbitron MASER is a device which can be used to produce millimeter and submillimeter radiation. We have used this device to produce radiation up to a frequency of 1 THz. This device utilizes nonrelativistic electrons trapped in orbit around a positively charged central wire to produce this radiation. These electrons can be supplied by either a pulsed glow discharge or a hot oxide coated filament. If properly configured this device can also be used as a fast opening plasma switch.

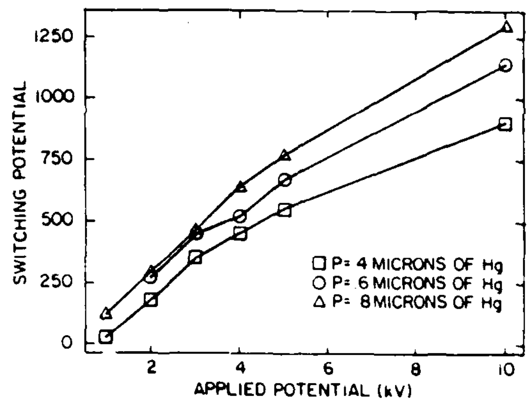

FIGURE 4

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A REVISED DERIVATION OF LANDAU DAMPING

Igor Alexeff and Mark Rader
University of Tennesee
Knoxville, Tennessee 37996-2100

Abstract

We rederive Landau's damping equation using an alternate method than that of original author. This alternate method results in a factor of 2 greater damping. This factor of 2 is a result of inconsistent assumptions by Landau about the nature of the singularity.

Introduction

In 1946, Lev Landau expanded[1], Vlasov's early paper on wave propagation in an ionized gas.[2] In this paper Landau first derived the terms of Vlasov's equation and then went on to continue the expansion of Vlasov's equation to recover the damping terms caused by a complex pole near the ω axis in the complex plane. The derivation of Landau Damping can be made without the use of a complex pole.[3] However, we rederive Landau's original damping term using a more rigorous and complete method.

In our derivation of Landau Damping, the contour of integration is forced to make a complete circle around the pole to avoid an infinite term. Landau, however assumed the pole is close enough to the axis of integration that it could be shifted to lie along this axis. He then took a semicircular contour around the pole, and so got half the value (half the damping) that we do[1]. He also ignored the fact that the singularity is a double pole.

If we carefully examine Landau's derivation, we find that he assumed the unperturbed distribution function $f_0(v)$ goes to zero before $v = \omega/k$ when he evaluated the real part of the wave equation. Thus he avoided the infinite term that we were forced to deal with. On the other hand, he assumed that $f_0(v)$ does <u>not</u> go to zero before $v = \omega/k$ when he evaluated the imaginary part of the wave equation. Thus, by using two mutually inconsistent assumptions, he both avoided the singularity and obtained a lower value for damping.

Kinetic Equations of Motion

The simplest way to recover Landau's damping term is to begin with the kinetic equations of motion, using the coordinate system shown in Figure 1a. In one dimension, let the particle distribution function f (x, v, t) be

$$f(x, v, t) = f_0(v) + f_1(x, v, t) \tag{1}$$

where f_0 is the unperturbed Maxwellian distribution function with base number density n_0 and f_1 is a small perturbation such that f_0 is much larger than f_1. If we assume that the plasma is collisionless, the kinetic equation of motion can be written as

$$\frac{\partial f}{\partial t} + v \cdot \nabla f - \frac{Ze}{m} \nabla \phi \frac{\partial f}{\partial v} = 0 \tag{2}$$

Where ϕ is the local electric potential Ze is the sign and charge of the particle and m is the particle mass. Substituting equation 1 into equation 2 yields that

$$\frac{\partial f_1}{\partial t} + v \frac{\partial f_1}{\partial x} - \frac{Ze}{m} \frac{\partial V}{\partial x} \frac{\partial}{\partial v} (f_0 + f_1) = 0 \tag{3}$$

where $-\partial V/\partial x$ is the electric field in the x direction. Since f_0 is much bigger than f_1, the f_1 function can be neglected in the third term giving that

$$\frac{\partial f_1}{\partial t} + v \frac{\partial f_1}{\partial x} - \frac{Ze}{m} \frac{\partial f_0}{\partial v} \frac{\partial V}{\partial x} = 0 \tag{4}$$

where v is the unperturbed particle velocity. It is also possible to write the Laplcian gradient in the electric potential, $\nabla^2 V$, in terms of the local perturbed electron density density distribution (f_1) since the bulk electron distribution function (f_0) is balanced by the ion distribution function. This gives that

$$\nabla^2 V = -\frac{Ze}{\varepsilon_0}\int_c f_1\, dx_1 \tag{5}$$

where ε_0 is the permitivity of free space and c is the contour of integration, which ranges from $-\infty$ to ∞ and is shown in figure 1a.

We can assume a functional dependence for the voltage and perturbed distribution function of the form $e^{i(kx-\omega t)}$. This gives us that

$$V = V_0 e^{i(kx - \omega t)} \tag{6}$$

and that

$$f_1 = f_{10} e^{i(kx - \omega t)} \tag{7}$$

If we differentiate these equations and insert the results into equations 4 and 5, we get that

$$k^2 V_0 = \frac{Ze}{\varepsilon_0}\int_c f_{10}\, dv \tag{8}$$

and that

$$f_{10}(kv - \omega) = -\frac{Ze}{m} k V_0 \frac{\partial f_0}{\partial v} \tag{9}$$

We can combine these two equations and form a soluble integral equation which is dependent on the change in the particle distribution function with respect to velocity. These two equations combine to form

$$1 = \frac{-Z^2 e^2}{\varepsilon_0 m k^2}\int_c \frac{\partial f_0}{\partial v}\frac{1}{(\omega/k - v)}\, dv \tag{10}$$

where ω/k is the wave velocity. If we integrate the integral term equation 10 by parts, using $\partial f_0/\partial v$ as du and $1/(v - \omega/k)$ as the variables, one can find that

$$1 = \frac{Z^2 e^2}{\varepsilon_0 m k^2} \int_c f_0 \frac{1}{(\omega/k - v)^2} dv \tag{11}$$

This is only true if we define the contour such that it goes in a circular path, as in figure 1, to avoid the pole at $v = \omega/k$, where k is a complex number. Defining the path such as we have done in figure, 1a breaks the contour integral into two separate pieces. This transforms equation 11 into

$$1 = \frac{Z^2 e^2}{\varepsilon_0 m k^2} \left(\int_{-\infty}^{\infty} f_0(v) \frac{1}{(\omega/k - v)^2} dv + \oint_{1/2\pi}^{5/2\pi} f_0(v) \frac{1}{(\omega/k - v)^2} dv \right) \tag{12}$$

where the first integral gives us the terms of Vlasov's equation and the second gives us the Landau damping terms.

Vlasov's Equation

If we look at the first integral in equation 12, one can expand the denominator term into an infinite series of terms. Thus if we expand this denominator term in terms of kv/ω, and pull out the constant n_0 term from the $f_0(v)$ equation, this equation becomes

$$1 = \frac{Z^2 e^2 n_0}{\varepsilon_0 m k^2} \frac{k^2}{\omega^2} \int_{-\infty}^{\infty} f_0(v) \left(1 + 2 \frac{kv}{\omega} + 3 \frac{k^2 v^2}{\omega^2} + \ldots \right) dv \tag{13}$$

where the constant in front of the integral can be found to be the plasma frequency, ω_p. This integral can be evaluated term by term, where the integral of the first term is unity, the integral of second is zero, the integral of third is $3\, k^2\, \bar{v}^2/\omega^2$, and the rest of the higher order terms can be neglected since they contribute very little to the solution. So that equation 13 becomes

$$1 = \frac{\omega_p^2}{\omega^2} \left(1 + 3 \frac{k^2 \bar{v}^2}{\omega^2} \right). \tag{14}$$

Thus we have evaluated the first part of equation 12 and also recovered the terms of Vlasov. We can remove constants in a similar way from the second integral to get it in a similar form. It is from this integral we get the imaginary coefficients for Landau Damping.

Landau Damping

If we look at the second integral in equation 12 we find it can also be expanded to form a second series, but we wish to expand this series about the point v equal ω/k. If we expand this series out, it can be found that

$$\frac{Z^2 e^2 n_0}{\varepsilon_0 m \omega^2} \oint_{1/2\pi}^{5/2\pi} f_0(v) \frac{1}{(1-(k\,v)/\omega)^2}\, dv = \frac{\omega_p^2}{\omega^2} \oint_{1/2\pi}^{5/2\pi} (f_0(\omega/k) + f_0(\omega/k)(v -$$

$$\omega/k) + \ldots) \frac{1}{(v-\omega/k)^2} \frac{\omega^2}{k^2}\, dv \tag{15}$$

where ω_p is the plasma frequency. This is a closed contour integral about a function which has been expanded into a Laurent series and this type integral can be easily evaluated using residue theory. This yields

$$\oint_{1/2\pi}^{5/2\pi} f_0(v) \frac{1}{(1-(k\,v)/\omega)^2}\, dv = 2\pi i\, f_0'(\omega/k) \frac{\omega^2}{k^2} \quad . \tag{16}$$

We can also integrate equation 15 directly to verify the results of equation 16. This is accomplished by letting $(v - \omega/k)$ be equal to $re^{i\phi}$. This can be substituted into equation 15 to yield that

$$\int_{1/2\pi}^{5/2\pi} (f(\omega/k) + f'(\omega/k)(re^{i\phi}) + \ldots)(re^{i\phi})^{-1}\, \omega^2 k^{-2} d\phi \ldots \tag{17}$$

where r is the distance from the singularity to the circular contour, and ϕ is the radian distance around the circle. If we integrate the first term we find

that the first term is zero due to symmetry, the second term is $2\pi i\, f'(\omega/k)\, \omega^2 k^{-2}$ and the higher order terms go to zero as the r goes to zero at this point.

We note that if a semicircular contour is taken, as did Landau, the first term becomes infinite as r goes to zero. A full circle contour is required to make the term zero by invoking periodic boundary conditions. This result is the same as that of equation 16.

At this point the inconsistency of Landau's treatment is revealed. He must integrate by parts to find the real part of the equation. However, he does not integrate by parts to find the imaginary part of the equation. This lack of integration of the imaginary part removes the singularity that we had to eliminate by using a complete circle.

The result of equation 17 and equation 14 will allow us to evaluate equation 12. If we insert these results into equation 12, we find that

$$\omega_p^2(1 + 3\, k^2 \bar{v}^2 \omega^{-2} + \omega^2 k^{-2} 2\pi i\, f_0'(\omega/k)) = 1 \tag{18}$$

If we let $\omega \sim \omega_p$ in the small second term, and $\omega = (\omega_r + i\, \omega_i)$ equation 18 becomes,

$$\omega_p^2 + 3\, k^2 \bar{v}^2 + 2\pi i \omega_p^2 \omega^2 k^{-2} f_0'(\omega/k) = \omega_r^2 + 2i\omega_r\omega_i - \omega_i^2 \tag{19}$$

where ω_r is the real part and ω_i is the imaginary part of the ω term.

To solve equation 19 let us make one last approximation. This approximation is that ω_r is much larger than ω_i. This allows us to easily separate the real and imiginary parts, so that equation 19 becomes

$$\omega_p^2 + 3\, k^2 \bar{v}^2 = \omega_r^2 \tag{20}$$

and

$$\pi\, \omega_r \omega_p^2 k^{-2} f_0'(\omega/k) = \omega_i \tag{21}$$

The ω_i of the above equations is equivalent to Landau's damping term, except it is greater in magnitude by a factor of + 2. We can derive the same results from our beam plasma equations as shown below. This factor of two discrepancy is due to the difference in the contour of integration.

Landau Damping Via Multibeam Interactions

It is possible to derive Landau damping in a much simpler way, using the multibeam plasma interaction. The well known equation for the beam plasma system is,

$$\sum_j \frac{\omega_{pj}^2}{(\omega - kv_{oj})^2} = 1 \tag{22}$$

where ω_{pj} is the plasma frequency of each beam and v_{oj} is the velocity of that beam.[3] We can let each beam be expressed in the form

$$\omega_{pj}^2 = \omega_p^2 f(v_j)\,\Delta v_j \tag{23}$$

where $f(v_j)$ is the distribution of function for each beam and

$$\sum_j f(v_j)\Delta v_j = 1 \ldots \tag{24}$$

If we insert eq. 23 into eq. 22 we get that,

$$\omega_p^2 \sum_j \frac{f(v_j)\,\Delta v_{oj}}{(\omega - kv_{oj})^2} = 1 \tag{25}$$

If we let $\Delta\, v_{oj}$ go to zero by letting the number of beams go to infinity, we approach a continuum. Then equation 25 can be expressed in an integral form, such that

$$\omega_p^2 \int_c \frac{f(v)\,dv}{(\omega - kv_o)^2} = 1 \tag{26}$$

We can let the distribution function "f(v)" be the unperturbed maxwellian distribution $f_o(v)$, and c be the contour of integration shown in figure 1a. This makes equation 26 equal to equation 11 and so it can be solved to yield the same results.

Landau's Derivation

In Landau's original paper on wave damping, he makes an incorrect approximation on the location, and nature of the singularity. Landau assumes that the function f_0 cuts off so rapidly that there is no contribution from $v = \omega/k$. Yet he finds an important contribution from $\partial f/\partial v$ at $v = \omega/k$!

Note that there is a double pole at $\omega/k = v$ before he does the computation. If he does a contour on a half circle, he gets,

$$\int_{\pi}^{2\pi} \frac{f_0}{(re^{i\phi})^2}\, r i e^{i\phi}\, d\phi = \int_{\pi}^{2\pi} \frac{f_0\, i\, d\phi}{(re^{i\phi})^2} \;;$$

Lim $r \to 0$ is ∞! Thus, no matter how small f_0 is at $v = \omega/k$, the result is that the only way to avoid the value ∞ is to use a periodic boundary conditions by going in a full circle around the pole. Then the above integral is identically zero. However, by using the full circle in this problem, the damping term, the imaginary term doubles in magnitude. Thus, Landau's original term was a factor of two low.

The basic philosophical point is that Landau assumed that the distribution function f_0 nonzero at $\omega/k = v$ to recover the imaginary term, but assumed that the same distribution function f_0 was identically zero at the same point to avoid an infinite, real term. The only way this case might have been possible is to have a singular distribution function in which $\partial f_0/\partial v < 0$, and $f_0 = 0$ at the same point, which implies a negative distribution function near ω/k. A negative distribution is obviously unphysical!

We discovered the above mathematical inconsistency, by using the multibeam derivation, described in the later portion of this paper. Using this method, the inconsistency is obvious.

Conclusion

In our rederivation of Landau Damping, we have shown that it is possible to derive the results of Landau from both multibeam interactions and kinetic theory in a simple and more direct manner. We have also found that, while Landau's work is essentially correct, the path he took to integrate around the singularity is mathematically incorrect due to the nature of the singularity, and it's position with respect to the main path of integration.

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M.G. Niimura and R.J. Churchill
American Research Corporation of Virginia, Radford, VA.*

and

I. Alexeff, F. Dyer, and M. Rader
University of Tennessee, Knoxville, TN.**

ABSTRACT

A rugged, compact, battery-powered millimeterwave (mm-wave) radar has been developed by using a prototype orbitron maser as the source. The orbitron maser was found suitable for such an application since it is high power, wideband (thus multi-channel) and frequency tunable. The radiation emanating directly from the tube was fairly uniform and the divergence angle (10°) was diffraction-limited. The orbitron pulse had a fast risetime (100ns), short pulsewidth (500ns) and no spurious oscillations. The orbitron output power was 6.7W minimum (possibly ~6.7kW due to the detector saturation and 400kW input power) at the V-band (50-75GHz). The power levels were similar at lower bands and constant up to 10Hz of repetition frequency. An innovative DC-DC converter was used to amplify 24V of battery potential up to 1000 times. The orbitron maser was characterized by simultaneous measurements of the applied voltage, discharge current (thus input-power and plasma-resistance), luminousity and wave signal. A linear scaling law was found for the mm-wave power to increase with the discharge current. Output power with hydrogen was twice to that observed with air or nitrogen working gases.

INTRODUCTION

Since the invention of a practical radar source (cavity magnetron) in 1940, research efforts have been concentrated on producing shorter wavelengths as well as higher power. Higher frequencies naturally increase the bandwidth and angular resolution, while reducing the size, of radar. However, the ability to tune the radar frequency over a wide range is often more important for various applications. The orbitron maser [1] is a wideband (1GHz~1THz) source able to scan the fundamental frequency (f_0) by changing the applied voltage (V_0):

$$f_0 = \frac{6.67\times10^4}{r(m)}\left(V_0(V) / \ln(\frac{r_2}{r_1})\right)^{1/2} = 1.5\sqrt{V_0(V)} \quad [\mathrm{GHz}]$$

Here, r_2/r_1 (typically 500) is the ratio of tube radius to the radius of the center conductor and the last term is the case $r=r_1=1.5$mil tungsten wire. Orbitron is a broadband oscillator even with fixed V_0 because the radius, r, of the rotating electron beam is continuous in the interval $r_1 \le r \le r_2$. Therefore, a multichannel radar may be constructed as shown in Fig.1. Alternatively, one can use multiple orbitrons, since the tube can be fabricated inexpensively. Upper and lower frequencies of the each tube may be varied by using wire of different radii and radial plungers of different depths, respectively. Large power handling capability of orbitron is also a great advantage which is not available in solid-state sources, although both are compact. Being free from the dissipation/isolation problems, significantly higher input current/voltage is permissible in orbitrons, indicating feasibility of constructing a high power/frequency radar in a compact dimension. Seald-off orbitron tubes and a portable power supply have been developed for the field-use of orbitron maser radar. Figure 2 shows the battery-powered high-voltage DC source able to apply max. 24kV-DC pulses on the orbitron tube (located in the right hand side of figure).

EXPERIMENTAL RESULTS

The potential across the orbitron (V_{0B} in Fig.2) changes as shown in the upper traces of Figure 3, when the tube is at (a) vacuum, (b) low pressure, and (c) high pressure. The lower traces are mm-wave signals. The voltage drop is due to a rise of the discharge current as becomes clear in Figure 4, where the wave forms of (a) applied voltage, (b) mm-wave signal, and (c) plasma luminousity are shown in reference to that of current (measured by C.T. in Fig.2). Obviously, the mm-wave emission results during the glow-to-arc transition, when the plasma luminousity enhances as shown in Fig.4-c. The risetime of mm-wave signal is the fastest of all. There seems to exist a current threshold for the emission of radiation as is evidenced in the expanded (lower) oscillogram in Figure 5 (the upper traces: mm-wave and lower traces: current). According to Figure 6, the hydrogen gives the maximum output at higher pressures (which is twice higher) than the case of the other gases. Thus, hydrogen is favorable for long-useful-life sealed-off orbitrons. Next, the mm-wave power was plotted with respect to the discharge current in Figure 7. Here, encouraging linear scaling is evident untill a saturation occurs with large currents. Simultaneous voltage and current measurements can give information on input power and plasma resistivity as computed for 60mT in Figure 8. At the peak time (100ns) of mm-wave. the input power is ~400kW and the resistivity is ~200Ω. The resistivity decays exponentially as confirmed in Figure 9, more rapidly at 60mT than 30mT. The directionality was measured by a detector translating orthogonally to the orbitron axis. The angle of emission was 11° (with & without a horn antenna) as seen in Figure 10, which is close to the diffraction limited angle, $\theta = 1.22\lambda/D = 10°$, since $\lambda = 4.28$mm and D=30mm. Figure 11 shows typical radar pulses indicating a good reproducibility of ±16% and the average pulse height of 1V. This measurement was made by a crystal detector with sensitivity of 25V/W (or 40mW/V) and aperture of 6.7cm^2. The detector was located 1" away from the orbitron of 14cm long so that the power radiated for 4π angle would be 6.7W and that for 11° solid-angle be 100mW. These are the most conservative estimation (by 1000 times at least), since the detector was calibrated in 10mV range and is well-known to be saturated above 100mV. Figure 12 is a prototype, hand-held mm-wave radar equipped with an orbitron maser. Figure 13 shows results of a preliminary radar experiment, where transmission and reflection of mm-waves were measured through a water-vapor channel of 47cm long. Figure 14 shows effects of the pure axial magnetic field externally applied; (a) without and (b) with field. With field, the discharge starts earlier as in high pressure tube and no deterioration in signal. This is encouraging since the tapered magnetic field may be applied for future orbitrons in order to increase the energy conversion efficiency. 144

Acknowledgements

* Work supported in part by the US Army under contracts DAAD09-87-C-0029 and DAAH01-87-C-0923.
** Work supported by the Air Force Office of Scientific Research under contract 86-0100.

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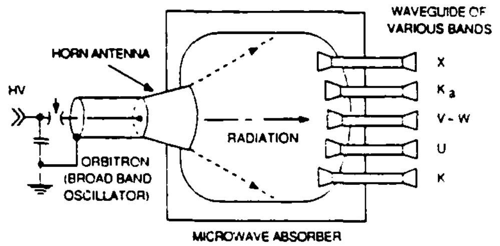


Figure 1

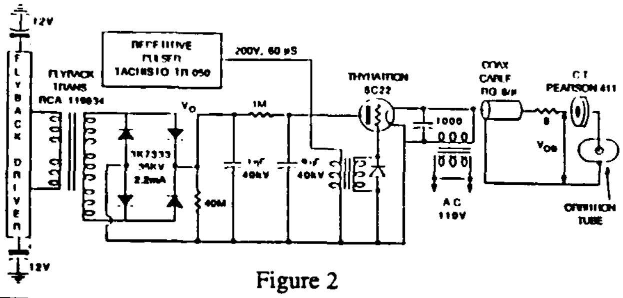
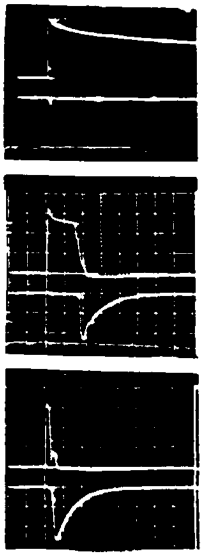


Figure 2

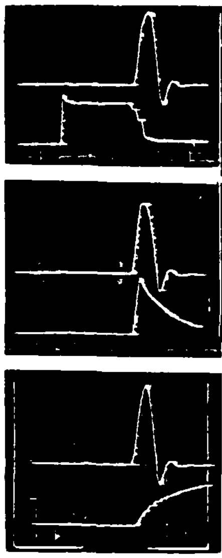


(a)

(b)

(c)

Figure 3



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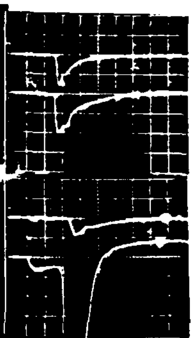


Figure 5

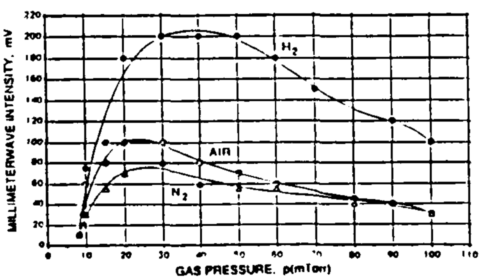
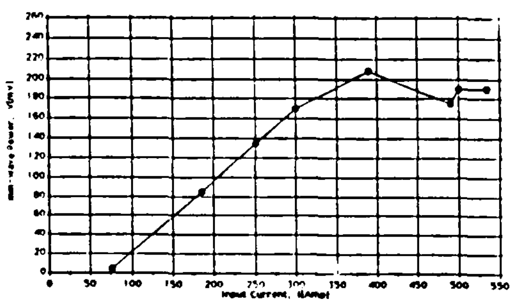


Figure 6



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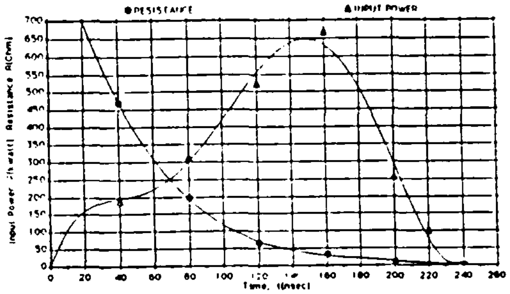


Figure 8

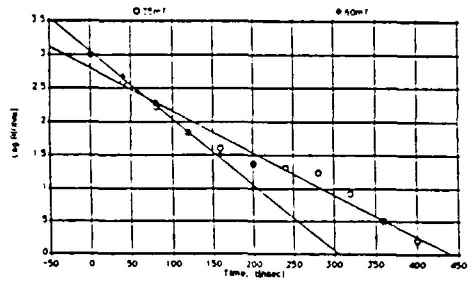


Figure 9

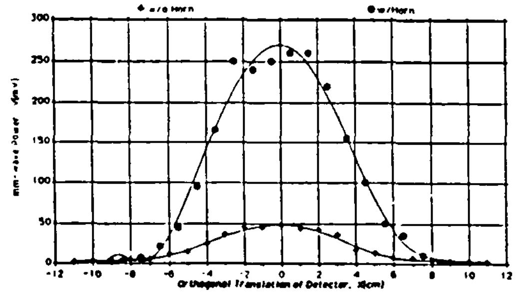
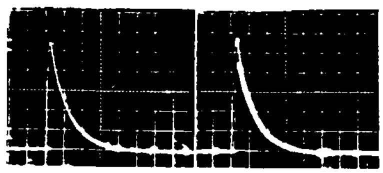


Figure 10



(a) (b)

Figure 11

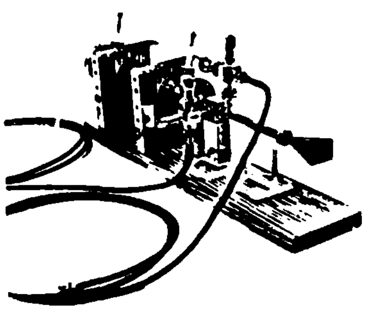
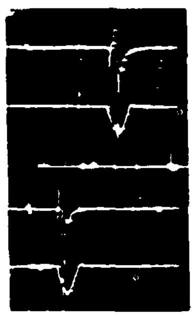


Figure 12



(a)

(b)

Figure 14

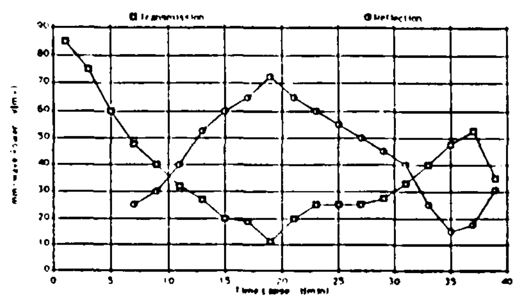


Figure 13

Pulsed and Steady-State Multianode Orbitron MASERs*

I. Alexeff, F. Dyer, and M. Rader
University of Tennessee
Knoxville TN, 37996-2100

Abstract

We have designed, built and tested several steady-state Orbitron MASERs, which have the unique property of having multiple anode wires. We have found that the multiwire structure increased the output power, efficiency, and reduced the heat loading of individual anode wires. We have also experimented with these devices in a pulsed mode and found similar results.

Introduction to the Orbitron MASER

The Orbitron MASER is a device, which can be used as a source of high frequency radiation. In its most basic physical form, it consists of a metal outer shell, which is cylindrical in form, and a thin metal wire, which is positioned along the axis of the metal shell. This basic device is shown in figure 1. This basic device can be described by an inner radius (r_0), which is the radius of the inner wire, and an outer radius (r_1), which is the radius of the outer shell.

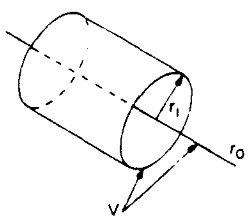


Figure 1

It is possible to produce high frequency rf radiation from such a simple device by applying a high potential between the inner wire, and outer shell. This must be done in such a way that the wire is biased positive with respect to the outer shell. The potential applied between the two surfaces creates a strong radial electric field, which will trap negatively charged particles in orbit around the positively biased wire. In this device the outer shell acts as a microwave cavity and the entire device resembles a coaxial line. These orbiting particles are negative mass unstable and couple to cavity modes within the shell-wire system. The frequency of this radiation (Ω) is proportional to the radius of the particle orbit, and the highest frequency at any particular voltage is proportional to the radius of the central wire. From solving the appropriate force balance equations we find that

$$\Omega = 1/r\ (ZeV / m_e \ln(r_1/r_0))^{\frac{1}{2}}$$

where V is the potential between the wire and shell, m_e is the electron mass, and Ze is the sign and charge of an electron.

The electron feed for the Orbitron MASER can be accomplished in one of two ways. Either by electrons sucked from a cold cathode discharge or a hot electron emitter, in a high vacuum. The first can be accomplished with relative ease since, for high wire potentials, the device operates on a short pulse basis and none of the interior parts experiences a large rise in temperature. However the hot cathode device, especially in the steady-state, often experiences a sharp increase in anode temperature. It has been theorized that a multiple wire anode structure should decrease the heat loading for each individual wire. If these wires are very closely spaced they should constructively couple and increase the output power for any given current. This is analogous to multiple atoms in a LASER.

Experimental Data From Multiwire Orbitrons.

In the first group of experiments involving a single wire Orbitron with a hot filament, open cavities between 5 and 10 cm in length were used with a diameter of between 1 and 2 cm. These cavities generated a series of harmonics for which the fundamental was determined by an external cavity cable resonance. We next increased the number of anode wires from one to two. This was done in the belief that this would increase the power output and the frequency range, which was indeed the case. Fig. 2 is a comparison between the spectral emission of one and two center wires. The pressure was at 5 X 10^{-6} torr and the voltage in the top spectral pictures was 1.2 kV, while at the bottom it was 800 V. Both had a current of about 34 mA on the center wire. Some nonharmonic frequencies can be seen in the two-wire spectral picture, as well as a series of harmonically related spectral lines. These nonharmonic emission lines disappear as the current or the voltage is increased, and so what appears to be phase locking occurs between the wires. The harmonic lines stay constant in frequency in both pictures, but change in amplitude.

The number of center wires was increased to four, arranged in a planer array, and the power and the apparent phase locking increased significantly, but more importantly, the upper limit of frequency emission went up sharply. Fig. 3 is an example of this. The input operating voltage to this device was 500 V, and the radius of the central wire was 3 mils or 0.075 mm. Under these operating conditions the highest circular frequency is 8.3 GHz, and so this is within a factor of 1.5 of the smallest computed orbit frequency for circular orbits.[2-3]

We next added water cooling to the outer cavity of the device, to reduce wall heating and arranging the central wires in a circular array. This had the same effect of reducing the wire heat load, but it also created a peculiar resonance in the system, as shown in figure 4. This resonance caused high frequency lines to appear at low voltages, but disappear at higher voltages. This resonance, we believe, is the result of a stabilization of the device caused by the introduction of a positive mass drift region. This region, located in the hollow anode structure, is caused by axisymetry of the anode structure.

During this experiment, we also tried pulsing the device to a high voltage, using a delay line to reduce spark gap noise and shape the pulse. This allowed us to produce x band radiation, as shown in figure 5, on an extended pulse basis from the device, yet have no visible heating of the central wires even at high repetition rates.

Conclusion

We have successfully demonstrated that the Orbitron can operate in a multiwire configuration. This multiwire configuration helps reduce heat load on the individual wires, improves the output frequency, and boosts the output power. A high frequency resonance can be achieved through the proper anode configuration. The Orbitron MASER can operate in a high vacuum and at the frequency range of its plasma filled counterparts.

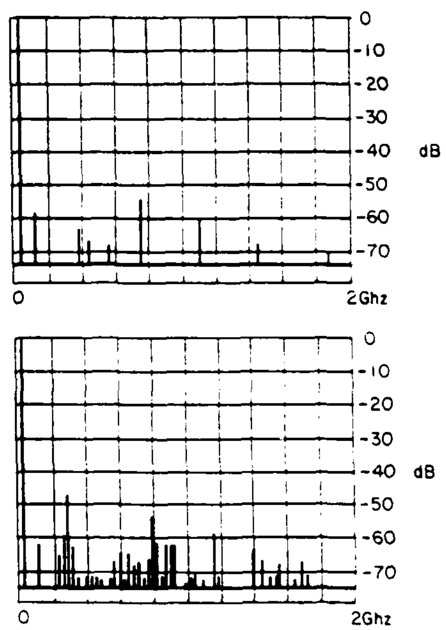
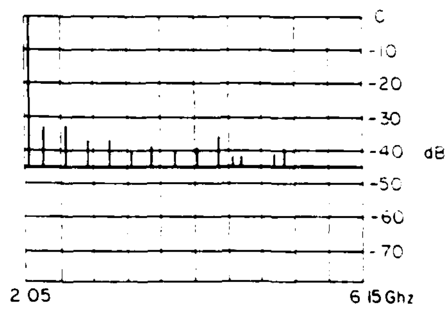


Figure .

* Work Supported by the Air Force Office of Scientific Reaserch under grant AFOSR-86 0100



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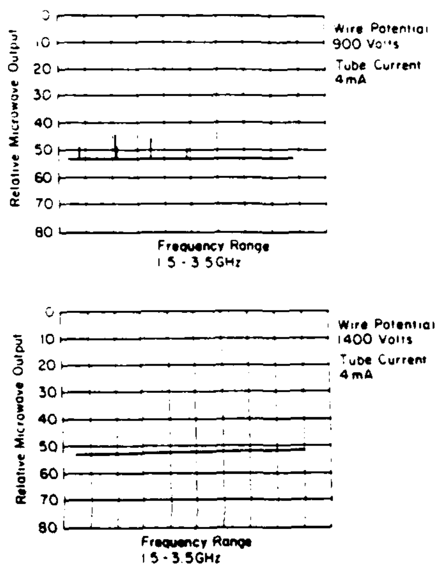

Figure 4

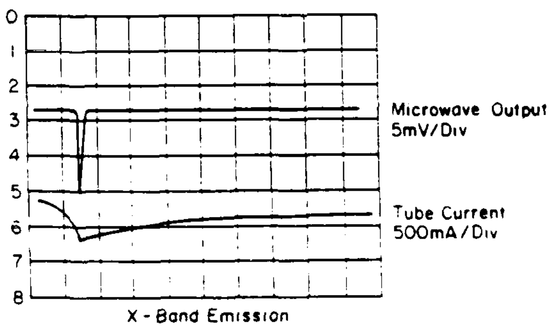

Figure 5

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APPENDIX F

**Bibliography of Oral and Poster Conference Presentations
Supported by Contract AFOSR 86-0100**

APPENDIX F

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9.	Fred Dyer, Mark Rader, and Igor Alexeff: "Constant Frequency Plasma Oscillations", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.	G-9
10.	Mark Rader, Fred Dyer, and Igor Alexeff: "Steady-State Operation of the High Vacuum Orbitron Maser", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.	G-10
11.	Igor Alexeff, Fred Dyer, and Mark Rader: "Probing the Pulsed Orbitron Glow Discharge", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.	G-11
12.	Laroussi, M. and Roth, J. R.: "Collisional Magnetic Pumping", Paper 5T7, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, June 1-3, Arlington, VA p. 103 (1987).	G-12
13.	Roth, J. R.: "Theory of Plasma Ion Implantation for Hardening Metals", Paper 6Y6, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, June 1-3, Arlington, VA p. 123-24 (1987).	G-13
14.	Alexeff, I.; Dyer, F.; and Rader, M.: "Time Dependent Frequency Shift in the Orbitron Maser", Paper 1C6, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, pp. 8-9 June 1-3, Arlington, VA, (1987).	G-14
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Publications **Page**

APPENDIX G

Abstracts of Oral and Poster Conference Presentations Supported by Contract AFOSR 86-0100

Igor Alexeff and J. Reece Roth, "A Simple MHD Model for Confinement Time Scaling in Tokamaks" Paper 2Q4, Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986) p. 38. ....

A Simple MHD Model for Confinement Time Scaling in Tokamaks*

Igor Alexeff and J. Reece Roth

Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

Experiments have demonstrated that the energy confinement time τ in tokamaks does not follow the classical scaling law prediction, $\tau \sim B^2/n$. We have developed a very simple scaling law based on MHD theory that predicts a confinement time scaling $\tau = Ca^2 T^{3/2}$, where T is the electron kinetic temperature, and a the plasma radius. The physical basis of this expression is the magnetic diffusivity of finite resistivity current filaments across the magnetic field.

The constant C in the above expression can be evaluated in two ways, both of which give similar values consistent with experiment. In one approach, we assume that a diamagnetic current impedes plasma expansion, and use Spitzer's expression for the resistivity appropriate to current flowing across the magnetic field.[1] In the second approach, we use the current along magnetic field lines which have a rotational transform. In this case, we use Spitzer resistivity along the field, which is lower, but note that the corresponding path length is longer and compensates. Our calculated confinement times account for the radial kinetic temperature (and conductivity) profile, and are longer (by a factor of 2-5) than quoted experimental energy containment times. Our scaling law was compared with a set of PLT measurements[2] (which included the $T_e(r)$ profile). Our scaling law gave confinement times a factor of 3 longer than the energy containment time measured.[2]

Our confinement time can be regarded as the skin depth penetration time for diamagnetic currents which balance the kinetic pressure of the plasma. The Bohr-van Leeuwen theorem states that a plasma will evolve through the operation of the second law of thermodynamics to a state of local classical kinetic equilibrium in which the diamagnetic currents are zero.[3,4] Our confinement time provides a measure of the time constant with which a plasma achieves this state of zero net diamagnetism.

*This work was supported by the Air Force Office of Scientific Research under contracts AFOSR-82-0045 (Alexeff) and AFOSR 81-0093 (Roth).

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Plasma Heating by Collisional Magnetic Pumping*

Mounir Laroussi and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

Collisional magnetic pumping[1] is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_0 (1 + \delta f(t))$, where f(t) is a bounded periodic function with a frequency below the ion cyclotron frequency. The transfer of energy between the perpendicular and parallel components of the ion velocity occurs through collisions. The change in the energy of the particles is governed by the following homogeneous linear differential equation with periodic coefficients,

$$\frac{d^2E}{dt^2} + \left[\frac{3}{2}\nu_c - \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right]\frac{dE}{dt} - \frac{\nu_c}{B}\frac{dB}{dt}E = 0$$

The above equation has been solved using Floquet's theory[2] along with a perturbation treatment. For the particular case where $f(t) = \cos \omega t$, the energy increase rate calculated[3] agrees with the one found by Berger et al.[4] The general case where f(t) is an arbitrary periodic function has been treated and a condition for a heating rate proportional to the first order of the field modulation $\delta = \Delta B/B_0$ is obtained. In this case we have

$$\frac{dE}{dt} = \delta\lambda_1 E_0$$

where

$$\lambda_1 = \frac{\nu_c}{T}\int_0^T e^{\frac{3}{2}\nu_c s}\left\{\frac{1}{1-\mathrm{Exp}\left(-\frac{3}{2}\nu_c T\right)}\int_0^T e^{-\frac{3}{2}\nu_c u} f'(u)\,du - \int_0^s e^{-\frac{3}{2}\nu_c u} f'(u)\,du\right\} ds$$

First order heating is possible because of the nonlinear relationship between the magnetic field and the energy increase rate. With a perturbation that keeps the magnetic moment under the exciter coil always larger than the background value, the net stochastic energy flow is unidirectional into parallel energy components.

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*Supported by AFOSR contract 81-0093 (Roth)

3C4

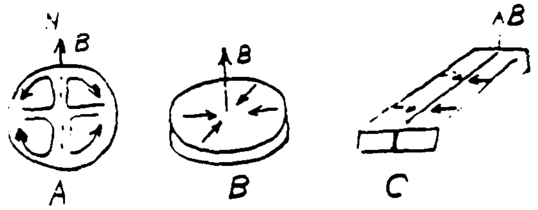
AN IMPROVED MHD MODEL FOR THE EARTH'S MAGNETIC FIELD*

Igor Alexeff and J. Reece Roth

University of Tennessee

A large literature exists concerning the origin of the Earth's magnetic field via a thermally-driven MHD generator.(1) The universal opinion is that a symmetric flow pattern cannot support a steady-state field. In this paper, we demonstrate that a symmetric flow can support a steady-state magnetic field, if the electrical conductivity of the magma is allowed to vary as a function of temperature. This is equivalent to variation as a function of radius in a planetary interior.

As a first assumption, we model the Earth's core as composed of two convection cells, as shown below in A. However, the return path flows over the surface of the



planet, where the temperature and conductivity is lower. Thus, the MHD effect of the return path can be to first order neglected. Our equivalent path is shown in B. For ease of computation, a slab model is shown in C.

The differential equation governing the flow is,

$$\frac{1}{\mu_0\sigma}\frac{\partial^2 B_z}{\partial y^2} + 2v_0 B_z\delta(y) + v_0\frac{\partial B_z}{\partial y}\,\mathrm{signum}(y) = \frac{\partial B_z}{\partial t}\,.$$

The first term is the standard diffusion term. The third term is Alfven's convection term. The second term is our new term, which corresponds to a source at the center.

The steady-state solution of this differential equation is, on the right half plane,

$$B_a = B_0 e^{-(v_0\sigma\mu_0)y} + B_1$$

which produces a steady-state narrow peak on axis. Use of known values of the core conductivity and flow rate produce a peak for B having a half-width about 10 km broad.

(1) For example, H.K. Moffatt, "Magnetic Field Generation in Electrically Conducting Fluids", Cambridge University Press, 1978.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-82-0045 (Alexeff) and office of Naval Research contract ONR N00014-80-C-0063 (Roth). (A preliminary version of this work was presented at this conference last year).

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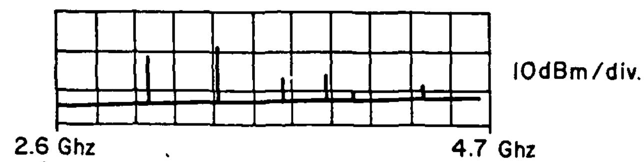
Steady-State, High-Vacuum
Operation of the Orbitron Maser.*

Mark Rader, Fred Dyer, and Igor Alexeff
University of Tennessee 37996-2100

We have operated our Orbitron Maser[1] in a high vacuum of 2×10^{-6} torr produced by an oil diffusion pump trapped by a liquid-nitrogen-cooled baffle. Electrons are supplied by an oxide-coated tungsten hot cathode placed inside the cylindrical cavity. To demonstrate that no plasma was present to produce plasma oscillations, as claimed by Schumacher and Harvey[2,3] we monitored the presence of plasma in the open cavity. The plasma-free emission corresponded to harmonically-related, steady-state, narrow lines. The fundamental (lowest frequency) line corresponded to a resonance in the cavity system, which could be observed with a grid-dip meter. The highest frequency line corresponded to 10GHz, which is about the frequency of an electron just grazing the wire in a circular orbit at the voltage used (600 volts).

To obtain these results, we use multiple anode wires (up to 7) to increase the space-charge limited current. Apparently, mode-locking between electrons on adjacent wires occurs. We have also been able to frequency-tune (pull) the resonant lines by adjusting anode voltage. Finally, we have suppressed the lower-frequency lines by excluding large-orbit electrons from the device.

TYPICAL HIGH FREQUENCY ORBITRON SPECTRUM



In our pulsed gas-filled tubes, a much higher voltage can be used, as well as a thinner wire. In this mode of operation, sub-millimeter operation is routine, and we have obtained radiation[4] at 1 THz (0.3mm). Peak microwave power output is about 1.5 watts at 1 THz and about 50 watts at frequencies up to 100 GHz. Efficiency ranges from 10% at 3.5 GHz to 1×10^{-3}% at 1 THz.

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980).
   I. Alexeff, IEEE Trans. Plasma Sci. PS-12, 280 (1984).
   I. Alexeff, Phys. Fluids, 28, 1990, June, 1985.

2. R.W. Schumacher and R.J. Harvey, 1984 IEEE International Conference on Plasma Science, Conference Record, P 109, IEEE Publication No. 84CH 1958-8.

3. R.W. Schumacher and R.J. Harvey, Bull. A.P.S., 29, 1179, October, 1984.

4. Igor Alexeff, Fred Dyer and Wlodek Nakonieczny, International Journal of Infrared and Millimeter Waves. p. 481, 6, (7) 1985 (Plenum).

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-82-0045-Alexeff.

Mark Rader, Fred Dyer, and Igor Alexeff, "Steady-State, High Vacuum Operation of the Orbitron maser", Paper 4E8, Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986), p. 81.

5R REVIEW PAPER

Basic Plasma Science and High Power Microwave Generation.

I. Alexeff, Univ. of Tenn., Knoxville, TN.

Invited Review Paper: Igor Alexeff, "Basic Plasma Science and High Power Microwave Generation", Paper 5R, Proceedings of the 1986, International Conference on Plasma Science, May 19-21, 1986,Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986), p. 81.

Application of Magnetic Pumping to a Classical Penning Discharge*. MOUNIR LAROUSSI, and J. REECE ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville, TN 37996-2100 -- The Classical Penning discharge consists of a straight cylindrical plasma with a constant axial magnetic field. Magnetic pumping is achieved by wrapping an exciter coil of length L around the plasma. The confining magnetic field is then perturbed, $B = B_0 (1 + \delta f(t))$, where $f(t)$ is a periodic function. The differential equation describing the exchange of energy is

$$\frac{d^2E}{dt^2} + \left[\frac{3}{2}\nu_c - \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right]\frac{dE}{dt} - \frac{\nu_c}{B}\frac{dB}{dt} E = 0.$$

The above equation has been solved for two forms of the perturbing function f(t). For a sine-wave(1), the energy increase rate is proportional to δ^2. For a sawtooth(2), it is proportional to δ, and much larger in magnitude. A computer simulation was applied to yield the behavior of the energy components with time. A high Q parallel resonant circuit has been designed to generate the RF perturbed magnetic field.

(1) J. M. Berger, et al.: Physics of Fluids, Vol. 1, (1958) pp. 301-307.
(2) M. Laroussi, Proc. SSST, (1986), p. 475-480, IEEE ISSN 0094-2898.

*Supported by AFOSR contract 86-0100 (Roth)

Mounir Laroussi and J. Reece Roth: "Application of Magnetic Pumping to a Classical Penning Discharge", APS Bulletin, Vol. 31, No. 9, (1986), p. 1421.

Two-Channel, Low Cross-Talk Diagnostic System for Measuring Nonlinear Mode Coupling in a Turbulent Plasma*. JOHN E. CROWLEY and J. REECE ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville, Tennessee 37996-2100 -- A system has been designed which modifies the HP 3577A Network Anayzer so that arbitrary signals in the range from 500 kHz to 10 MHz can be compared in amplitude and phase. The system will be used to sample density or potential fluctuations at two points in a turbulent plasma, and measure the frequency, amplitude, and phase of signals detected by the probes. This modification is totally external to the HP 3577A Network Analyzer, and has been designed to minimize the cross-talk between the two channels, so that nonlinear mode coupling processes in the plasma can be distinguished from mode coupling (cross-talk) originating within the instrumentation itself. The composite system should have a dynamic range from 0 dBm to -80 dBm, cross-talk no more than -60 dB between channels, a maximum spurious response - 50 dB below the maximum input signal, and an amplitude and phase accuracy of 1 dB and 5 degrees, respectively.

*Supported by Contract AFOSR 86-0100 (ROTH).

John E. Crowley and J. Reece Roth: "Two-Channel, Low Cross-Talk Diagnostic System for Measuring Nonlinear Mode Coupling in a Turbulent Plasma" APS Bulletin, Vol. 31, No. 9 (1986) p. 1596.

Characterization of a Steady-State, Classical Penning Discharge*. J. E. BREEDING, M. E. IRWIN, A. KESHAVARZI, D. L. SAFFER, M. LAROUSSI, and J. R. ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville, TN 37996-2100. -- Our classical Penning discharge is operated in the steady state, and produces an approximately axially uniform plasma 80 cm long and 10 cm in diameter in a constant magnetic induction up to 0.4 T. This plasma is electric field dominated, with axial and radial electric fields up to several hundred volts per centimeter; exhibits E/B and grad B drift waves; is highly turbulent; emits broadband RF emission at the fundamental and harmonics of the geometric mean emission frequency, and at the electron plasma frequency; has number densities from 10^5 to $10^{11}/cm^3$; electron kinetic temperatures of a few tens of eV, and ion energies up to several keV. In this paper we report data on the continuity-equation oscillation in this plasma; statistical properties of its plasma turbulence; radial and axial profiles of the ion and electron kinetic temperatures, number density, and plasma potential; and the nature of the ion energy distribution function, as it is affected by the plasma operating conditions

*Supported by contract AFOSR 86-0100 (ROTH).

J. E. Breeding, M. E. Irwin, A. Keshavarzi, D. L. Shaffer, M. Laroussi, and J. R. Roth: "Characteristization of a Steady-State, Classical Penning Discharge", APS Bulletin, Vol. 31, No. 9 (1986) p. 1579.

Constant Frequency Plasma Oscillations*, FRED DYER, MARK RADER, and IGOR ALEXEFF, University of Tennessee 37996-2100 -- We have been observing a new and previously undetected steady-state spectral line being emitted from a device with the same basic design as our pulsed orbitron maser.[1] Upon investigation of these spectral lines we found that the fundamental (lowest frequency) line was the stable steady-state emission of the electron plasma frequency (ω_p). We believe that this frequency stability is caused by the continual flushing of ions from the system and their subsequent replacement by new ions. This flushing damps the instabilities, which cause the frequency drift seen in other ion plasma oscillators, before they form.

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980); I. Alexeff, Phys. Fluids, 28, 1990, June 1985.

*Work supported by the Air Force Office of Scientific Research under grant AFOSR-86-0100.

Fred Dyer, Mark Rader, and Igor Alexeff: "Constant Frequency Plasma Oscillations", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.

Steady-State Operation of the High Vacuum Orbitron Maser*, MARK RADER, FRED DYER, and IGOR ALEXEFF, University of Tennessee 37996-2100 -- We have operated our radial injection orbitron at a pressure of 1×10^{-6} torr[1]. Electrons are supplied to this system by means of an axial, oxide-coated hot tungsten filament. The plasma-free emission of this device corresponded to harmonically-related, steady-state, narrow lines unlike the results obtained by others[2]. Depending upon the device's design, the fundamental (lowest frequency) line corresponded either to a external resonance, or to a TEM cavity mode. Operation of these devices is routine in the 0 - 2 GHz frequency range. Frequencies as high as 1.5 GHz have been observed at the low operating voltage of 40 volts. To obtain these results, we have used multiple anode wires (up to 7) to increase the space-charge limited current, and apparent mode-locking between electrons orbiting adjacent wires occurs.

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980); I. Alexeff, Phys. Fluids, 28, 1990, June 1985.
2. R. W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October, 1984.

*Work supported by the Air Force Office of Scientific Research under grant AFOSR-86-0100.

Mark Rader, Fred Dyer, and Igor Alexeff: "Steady-State Operation of the High Vacuum Orbitron Maser", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.

Probing the Pulsed Orbitron Glow Discharge*, IGOR ALEXEFF, FRED DYER, and MARK RADER, University of Tennessee 37996-2100 -- To study the suggestion that the pulsed Orbitron emission[1] is due to plasma oscillations[2], we have probed the plasma with a microwave signal from an external oscillator. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a wavelength of 4 mm or shorter, with a penetrating beam at 9 mm. This suggests that under specific conditions, plasma oscillations are not the emission mechanism. Similar conclusions have been obtained by using both passive optical probing, and a Langmuir Probe.

1. I. Alexeff. Phys. Fluids, 28, 1990, June 1985.
2. R. W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October, 1984; R. W. Schumacher and R. J. Harvey, 1984 IEEE International Conference on Plasma Science, Conference Record, P. 109, IEEE Publication No. 84ch 1958-8.

*Work supported by the Air Force Office of Scientific Research under grant AFOSR-86-0100.

Igor Alexeff, Fred Dyer, and Mark Rader: "Probing the Pulsed Orbitron Glow Discharge", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.

5T7 Collisional Magnetic Pumping*

Mounir Laroussi and J. Reece Roth
UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, TN 37996-2100

ABSTRACT

This paper describes the application of collisional magnetic pumping[1,2] to heat a plasma, and provides new results relating to the energy transfer process between the RF perturbed magnetic field and the parallel and perpendicular energy components of the heated species. From numerical solutions to the energy transfer problem, it has been found that there exists a plasma parameter regime in which collisional magnetic pumping is most effective, and for each collision frequency ν_c there exists an optimum driving frequency ν which maximizes the energy transfer from the perpendicular component of the ion and electron motion to the parallel components. It has also been found that there exists a threshold in the parameter $\nu_c T$, where T is the period of the driving frequency, below which the parallel component of the energy saturates after an initial transient phase, and the collisional magnetic pumping is no longer effective. The heating rates for different forms of the perturbing function f(t), including a sawtooth and a triangular function, have been found theoretically[3] and compared to that of other selected RF heating methods including ICRH and ECRH.

The high Q parallel resonant circuit required to generate the broadband RF perturbed field will be described along with the experimental results on the power absorption. The experiment is performed on a classical Penning discharge with an axially uniform, steady state magnetic field. This field is RF perturbed by wrapping an exciter coil of length L around the plasma. The magnetic field under the coil assumes the form $B = B_0 (1 + \delta f(t))$ where B_0 is the background static field, δ the field modulation and f(t) the perturbing function. The heating rate is plotted against various plasma parameters and its dependence on the field modulation is established.

1. J. M. Berger, *et. al.*: Physics of Fluids, Vol. 1, No. 4 (1958) pp. 301-307.
2. M. Laroussi, "Plasma Heating by Collisional Magnetic Pumping". 18th Southeastern Symposium on System Theory, April 7-8, 1986.
3. M. Laroussi and J. Reece Roth, "Application of Magnetic Pumping to a Classical Penning Discharge". APS Bulletin, Vol. 31, No. 9, p. 1421, (1986).

*Supported by AFOSR contract 86-0100 (Roth)

Laroussi, M. and Roth, J. R.: "Collisional Magnetic Pumping", Paper 5T7, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, June 1-3, Arlington, VA p. 103 (1987).

THEORY OF PLASMA ION IMPLANTATION FOR HARDENING METALS*

Prof. J. Reece Roth
UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

ABSTRACT

A problem with existing methods of hardening metals by ion implantation is that the ion beams normally used do not lend themselves to implanting the ions uniformly on complex surfaces such as gear teeth, screw threads, turbine blades, etc. If one inserts a metallic sample into a plasma and biases it negatively, deep into the ion saturation region as though it were a Langmuir probe, the surface of the sample will be isotropically bombarded by ions over scale sizes larger than the local Debye length. If the sample is biased to negative potentials of 50 kV or more, useful amounts of ion implantation can occur in very short times in samples such as spheres and gear teeth[1,2]. Ion energies of about 50 keV normally lead to implantation depths of a tenth of a micron or so at room temperature, but it seems that ions implanted at these energies manage to migrate ahead of the wear surface and maintain surface hardness even after several tenths of a micron of surface material are worn away[2].

This paper examines the plasma parameters required to achieve a given level of ion implantation in complex metal objects, how to calculate exposure times, energy requirements, and other commercially significant factors in the application of this new process. It is shown that the surface fluxes of 50 keV ions from plasma ion implantation can exceed those from space charge limited ion beam sources; that relatively modest and easily generated steady-state plasmas can isotropically bombard samples with a Debye length and scale size of less than 0.5 mm; that an exposure time of only a few seconds is required to produce useful levels of ion implantation; that the power delivered to the sample can be made much smaller than the level required to melt it; that by pulsing the high negative biasing voltage on and off with an appropriate duty cycle, the ions required for implantation on a sample of several tens of square centimeters will not significantly deplete a relatively modest plasma; and that the total power and energy required to achieve a given level of hardness by plasma ion implantation is far below that required by conventional foundry techniques.

1. J. Bell, R. Herman, and C. Sutton, New Scientist, March 6, 1986, pp. 34-36.
2. Private communication, Dr. John R. Conrad, Univ. of Wisconsin, August, 1986.

***Supported in part by ONR contract N00014-80-C-0063 and by contract AFOSR 86-0100 (Roth).**

Roth, J. R.: "Theory of Plasma Ion Implantation for Hardening Metals", Paper 6Y6, Proceedings of the 1987 IEEE International Conference on Plasma Science, June 1-3, 1987, Alington, VA, IEEE Catalog #87CH2451-3 (1987) pp. 123-24.

1C6

TIME DEPENDENT FREQUENCY SHIFT IN THE ORBITRON MASER* Igor Alexeff, Fred Dyer, Mark Rader, University of Tennessee 37996-2100:

It has been observed by both ourselves and others[1], that the frequency output in our pulsed Orbitron maser chirps upward in time as the discharge voltage declines. This is explained by the way the Orbitron operates. The Orbitron maser[2] is a device in which electrons orbit a positively charged central wire placed on axis in a cavity resonator. The rotating electrons couple to microwave cavity modes and generate RF radiation. These electrons are born on the outer edge of the cavity-wire system and drift inward. Since the frequency output of the electron is inversely proportional to the electron radius in the system, and the electron cloud must move inward into the potential well to obtain the work required for microwave emission, one would expect to see a shift upward in frequency as the pulse progresses even though the potential well is collapsing.

We have predicted this upward frequency chirp from the basic theory of this device and have found it to be in good agreement with what we experimentally observe. Using standard charcteristics of these devices, the chirp rate has been found to be 3.55 x 10^{17} Hertz per second, and in a characteristic experiment, using a device of the same dimensions as was used in our calculations, we get a chirp rate of 5.5 x 10^{17} Hertz per second

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

1. R.W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October, 1984: R. W. Schumacher and R. J. Harvey, 1984 IEEE Internatoinal Conference on Plasma Science, Conference Record, P 109. IEEE Publication No 84ch 1958-8: Private conversation with R. W. Schumacher.
2. I. Alexeff, Phys. Fluids, 28, 1990, June 1985.

Alexeff, I.; Dyer, F.; and Rader, M.: "Time Dependent Frequency Shift in the Orbitron Maser", Paper 1C6, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, pp. 8-9 June 1-3, Arlington, VA, (1987).

1C5

CROSS SECTIONAL NUMBER DENSITY IN THE PULSED ORBITRON MASER* Mark Rader, Igor Alexeff and Fred Dyer, University of Tennessee 37996-2100

To study the suggestion that the pulsed Orbitron emission[1] is due to plasma oscillations[2], we have probed the plasma with a microwave signal from an external oscillator. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a frequency of 133 GHz or higher, with a penetrating beam at 36 GHz. This gives a emission to bulk plasma frequency ratio of 3.7 to 1. We have also used a radially adjustable Langmuir Probe to study the electron number density at points across the discharge radius. The peak electron plasma frequency in this device at a radius of 40 mils (1 mm) was found to be about 10.6 GHz. The peak frequency emitted by this device was found to be 38 GHz. This gives a peak emission to peak plasma frequency ratio of 3.6 to 1. The peak number density occurs between .5 to 1 microseconds after the peak emission occures.

The electron temperature at this point was about 25 eV with a plasma potential (V_p) of 150 V. Since the Orbitron maser is a coaxial system with a positively charged wire at the center, 10 kV in this case, this plasma potential indicates a potential well for electron trapping.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100

1. I. Alexeff, Phys. Fluids, 28, 1990, June 1985.
2. R. W. Schumacher and R. J. Harvey, Bull. A.P."S., 29, 1179, October, 1984: R. W. Schumacher and R. J. Harvey, 1984 IEEE International Conference on Plasma Science, Conference Record, P 109, IEEE Publication No 84ch 1958-8.

Rader, M.; Alexeff, I.; and Dyer, F.: "Cross Sectional Number Density in the Pulsed Orbitron Maser", Paper 1C5, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, pp. 8-9 June 1-3, Arlington, VA, (1987).

9R 18 Analytical, Computational, and Experimental Results on Plasma Heating by Collisional Magnetic Pumping*. MOUNIR LAROUSSI and J. REECE ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville, TN 37996-2100 -- The equations describing the energy transfer between the RF field and the charged particles due to collisional magnetic pumping[1] are solved analytically and numerically for different RF magnetic field waveforms.[2] The results are then compared and an optimum working regime is found. If a sinewave perturbation is used with a field modulation factor of 10% and an initial particle energy of 10ev, which is typical of electrons in our plasma, the maximum energy increase is found to be about 3 10^{-2} ev per RF cycle. In the case of a sawtooth perturbation, the heating rate is found to be proportional to the first order of the field modulation factor, and the energy increase for the above conditions is about 67 10^{-2} ev per RF cycle. The experimental setups for both sinewave and sawtooth perturbation will be discussed along with the energy absorption measurement and a theory-experiment comparison.

*Supported by contract AFOSR 86-0100 (Roth).

1. J. M. Berger, et al., Physics of Fluids, Vol. 1, (1958), pp. 301-307.
2. M. Laroussi, and J. R. Roth, 14th IEEE Int. Conf. on Plasma Science, IEEE No. 87CH2451-3 (1987), p. 103.

Laroussi, M. and Roth, J. R.: "Analytical, Computational, and Exerimental Results on Plasma Heating by Collisional Magnetic Pumping", APS Bulletin, Vol. 32, No. 9 (1987) p. 1950.

1E 9 Average and Cross Sectional Number Densities in the Orbitron Maser*, Mark Rader, Fred Dyer, and Igor Alexeff, University of Tennessee, 37996-2100:

In order to better understand the pulsed glow Orbitron MASER, we have been using a penetrating microwave beam to make bulk measurement of the number density in the plasma. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a frequeny of 250 GHz or higher, while a microwave beam at 37.5 GHz was penetrating the glow discharge. This gives a emission to bulk plasma frequency ratio of 6.7 to 1. We have also used a radially inserted Langmuir probe to measure both the electron number density across the plasma chord and the electron temperature. From this probe we found the peak electron plasma frequency in this device at a distance of 40 mils (1 mm) from the central wire was about 10.6 GHz. The peak frequency emitted by this device was found to be 38 GHz. This gives a peak emission to peak plasma frequency ratio of 3.6 to 1. These and other experimental results lead us to conclude that the emitted frequency is apparently not related to the electron plasma frequency.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

Rader, M.; Dyer, F.; and Alexeff, I.: "Average and Cross Sectional Number Densities in the Orbitron Maser", APS Bulletin, Vol. 32, No. 9 (1987) p. 1714.

1E 10

Upward Frequency Shifts with Declining Anode Voltage in the Orbitron MASER* Fred Dyer, Mark Rader, and Igor Alexeff, University of Tennessee 37996-2100:

It has been observed that the frequency output in our pulsed Orbitron MASER chiprs upward in time even though the anode voltage is decreasing. This can be explained by the physics of the Orbitron MASER. The Orbitron MASER[1] is a device in which electrons orbit a positively charged central wire placed on axis in a cavity resonator. The rotating electrons couple to microwave cavity modes and generate RF radiation. These electrons are born on the outer edges of the cavity-wire system and spiral inwards. In this device the frequency output of the electrons is inversely proportional to the electron radius in the system, and is only related to the square root of the difference in potential between the anode and cavity wall. Since the electrons spiral inward during each pulse, one would expect to see a shift upward in frequency as the pulse progresses even though the potential well is collapsing. We have predicted this upward frequency chirp from the basic theory of this device and have found it to be in good agreement with what we experimentally observe. Using standard characteristics of these devices the chirp rate has been found to be 3.55×10^{17} Hertz per second, and in a characteristic experiment, using a device of the same dimensions as was used in our calculations, we get a chirp rate of 5.5×10^{17} Hertz per second.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

1. I. Alexeff, Phys. Fluids, 28, 1990, June 1985.

Dyer, F.; Rader, M.; and Alexeff, I.: "Upward Frequency Shifts with Declining Anode Voltage in the Orbitron Maser", APS Bulletin, Vol. 32, no. 9 (1987) p. 1714 .

Laroussi, M. and Roth, J. R.; "Latest Experimental Results on the Application of Collisional Magnetic Pumping to Heat a Steady-State Plasma", Paper 1P2, Proceedings of the 1988 IEEE International Conference on Plasma Science, June 6-8, 1988, Seattle, Washington, IEEE Catalog No. 88CH2559-3 (1988) p. 36.

1P2

Latest Experimental Results on the Application of Collisional Magnetic Pumping to Heat a Steady State Plasma*

Mounir Laroussi and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

In previous work[1] we showed that collisional magnetic pumping[2] can be an efficient way to heat a plasma if the right magnetic field perturbation is used. A sinewave perturbation proved to achieve second order heating[1,2]. A sawtooth perturbation causes first order heating for small field modulation factors[1]. This proved to have an energy increase rate two to three orders of magnitude larger than the previous case.

An experimental attempt to observe heating is under progress. For this, two different apparatus have been designed, built, and tested. The first is a high-Q tunable parallel resonant circuit capable of generating a sinusoidal RF magnetic field. When applied to the plasma, this field adds an RF perturbation to the background DC magnetic field. The diagnostics used to probe the change in the energy of the particles due to collisional magnetic pumping are a Langmuir probe to measure the electron and ion temperature, a retarding potential analyser to monitor the particles energy distribution, and a network analyser to sense impedance changes due to energy absorption.

The second apparatus is a switching circuit capable of driving a current sawtooth through the exciter coil, which in turn generates a sawtooth magnetic field perturbation superimposed on the background magnetic field. The switch used is a TMOS (Metal-Oxide-Semiconductor) transistor capable of switching on and off in few tens of nanoseconds, and of sustaining high currents at relatively high voltages. The energy of the particles is diagnosed as mentioned above.

The experimental data along with the detailed design of the above apparatus will be presented and discussed.

1. M. Laroussi and J. R. Roth, APS Bulletin, Vol. 32, No. 9, p. 1950, (1987).

2. J. M. Berger, et al., Physics of Fluids, Vol. 1, No. 4, pp. 301-307, (1958).

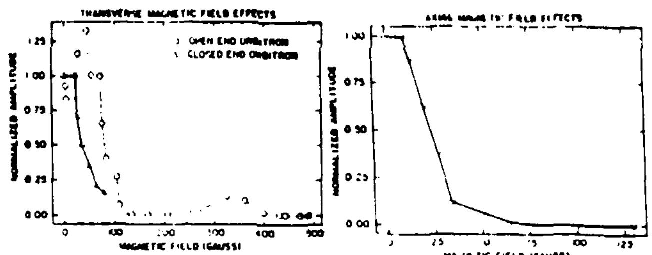
*Supported by AFOSR contract 86-0100(Roth).

3C3

Magnetic Output Control, and External Frequency Control of the Orbitron MASER*

Igor Alexeff, Fred Dyer, and Mark Rader
University of Tennessee
Knoxville, TN 37996-2100

The Orbitron MASER is a negative mass unstable device in which electrons orbit a positively charged wire. It has a unique feature, in that no external magnetic field is required. We have been studying the effect an external magnetic field has on the RF output of this device. The effect was studied for two cases, one in which the field was parallel to the axis of electron rotation, and the other in which the field was perpendicular to this axis. The field, in all cases, was varied between 0 and at least 100 Gauss. We found that, for all cases, the use of a small (on the order of 20 Gauss) externally applied field reduced the RF output of the device and that there was no significant RF output at fields over 100 Gauss[1] for both cases, in contrast to the results of others[2]. The relative output verses magnetic field, for both cases, is shown below. The outer radius of this device was approximately 1 cm. We also found that the field required suppress the instability was inversely proportional to the radius of the outer cavity.



The power for this device is supplied by capacitor bank, which is switched by an adjustable spark gap. We have found that it is possible to control the output spectra of this device by varying the capacitance of this bank. By reducing this capacitance to the proper level, it is possible suppress the lower frequencies emitted, while leaving the higher frequencies relatively unchanged.

1. F. Dyer, I. Alexeff, H. F. Karimy, and W. Nakonieczny, 1984 IEEE International Conference On Plasma Science, Pg 109, IEEE Pub # 84CH1958-8
I. Alexeff, Bull. A.P.S. 26, #7, Pg 1046 October 1981

2. R. W. Schumacher and R. J. Harvey, 1984 IEEE Conference on Plasma Science, Pg 109 IEEE Pub # 84CH1958-8

* Work Supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100

Alexeff, I.; Dyer, F.; and Rader, M.: "Magnetic Output Control, and External Frequency Control of the Orbitron Maser", Paper 3C3, Proceedings of the 1988 IEEE International Conference on Plasma Science, June 6-8, 1988, Seattle, WA, IEEE Catalog No. 88CH2559-3 (1988) p. 72.

Experimental Results on Collisional Magnetic Pumping in a Modified Penning Discharge with Magnetic Mirror Configuration.* MIN WU, L. JIANG, and J. R. ROTH, University of Tennessee, Knoxville TN 37996-2100 -- This paper describes the application of collisional magnetic pumping to heat a plasma[1,2], and provides new results relating to the energy transfer process between the RF perturbed magnetic field and the parallel and perpendicular energy components of the heated species in a modified Penning discharge apparatus with a magnetic mirror configuration. A switching circuit capable of driving a current sawtooth through the exciter coil was developed, which generates a sawtooth magnetic field perturbation superimposed on the background DC magnetic field. The diagnostics used to probe the change in the energy of the particles due to collisional magnetic pumping are a Langmuir probe to measure the electron kinetic temperature, a retarding potential analyser to monitor the ion energy distribution, and a network analyser to sense impedance changes due to energy absorption. The experimental data along with the detailed design of the above apparatus will be presented and discussed.

*Supported by AFOSR contract 86-0100 (Roth).

1. M. Laroussi and J. R. Roth, APS Bulletin, Vol. 32, No. 9, p. 1950, (1987)
2. J. M. Berger, et al., Physics of Fluids, Vol. 1, No. 4, pp. 301-307, (1958).

Wu, M.; Jiang, L. and Roth, J. R.: "Experimental Results on Collisional Magnetic Pumping in a Modified Penning Discharge with Magnetic Mirror Configuration", APS Bulletin, Vol. 33, No. 9 (1988) pp 2019-20.

Experimental Results of Microwave Absorption with Varying Magnetic Field in A Modified Penning Discharge.* L. JIANG, MIN WU, and J. R. ROTH, University of Tennessee, Knoxville TN 37996-2100 -- Microwave absorption in a varying magnetic field is investigated near electron cyclotron resonance[1] with a Hewlett Packard 8510 Network Analyzer which is capable of swept frequency measurements, and of measuring reflection and transmission coefficients from 0.045 to 18 GHz, with greater than 80 dB dynamic range. The experimental conditions are such that the plasma is generated in a modified Penning discharge in a magnetic mirror configuration. A Langmuir probe is used to measure electron number density and kinetic temperature. A microwave beam is caused to propagate along the axis of the magnetic mirror field in the plasma column. The microwave beam is attenuated near the electron cyclotron reasonance frequency, in the range of a few GHz microwave absorbtion. The attenuation, along with hot-plasma effects, are measured as a function of frequency by the Hewlett Packard 8510 Network Analyzer.

*Supported by AFOSR Contract 86-0100(Roth)

1. M. A. Heald and C. B. Wharton, Plasma Diagnostics with Microwaves, (1978) New York.

Jiang, L.; Wu, M. and Roth, J. R.: "Experimental Results of Microwave Absorption with Varying Magnetic Field in a Modified Penning Discharge", APS Bulletin, Vol. 33, No. 9 (1988) pp 119.

Magnetic Output Control and Self-Damping of the Orbitron MASER* Igor Alexeff, Fred Dyer, and Mark Rader, University of Tennessee -- The Orbitron MASER is a negative mass unstable device which has a unique feature, in that no external magnetic field is required. The effect of an external magnetic field was studied for two cases, one in which the field was parallel to the axis of electron rotation, and the other in which the field was perpendicular to this axis. We found that the use of a small (on the order of 20 Gauss) externally applied field reduced the RF output of the device and that there was no significant RF output at fields over 100 Gauss for both cases. We have also done some theoretical calculations based on the experimental magnetic field data. In these calculations, we predict that the current in the device reaches a level to produce a magnetic field of sufficient amplitude to kill the instability. We have confirmed this experimentally.

*Work Supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

Alexeff, I.; Dyer, F. and Rader, M.: "Magnetic Output Control and Self-Damping of the Orbitron MASER", APS Bulletin, Vol. 33, No. 9 (1988) pp 2008.

6F 8 Steady-State Operation of the Gas-Filled Orbitron Maser.* Mark Rader, Fred Dyer, James Carroll, and Igor Alexeff, The University of Tennessee. -- We have operated gas-filled, cold-cathode Orbitron Masers in the steady-state at low voltages (below 400 V) and low currents (below 40 mA). The emission spectrum consists of narrow lines that do not vary in frequency as the discharge pressure and current are changed. The highest frequency observed corresponds closely to that predicted from our simple orbit theory.[1] This suggests that the oscillations do not correspond to the plasma frequency, as claimed by others.[2]

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980).
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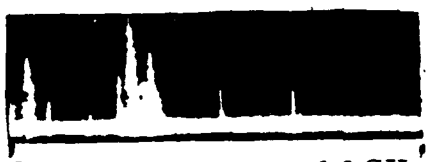
*Work supported by the Air Force Office of Scientific Research under grant #AF-AFOSR-86-0100.



Rader, M.; Dyer, F.; Carroll, J. and Alexeff, I.: "Steady-State Operation of the Gas-Filled Orbitron Maser", APS Bulletin, Vol. 33, No. 9 (1988) pp 2009.

Real Plasma Effects of Microwave Radiation Propagating Perpendicular to a Magnetized Plasma*

Lili Jiang and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, TN 37996-2100

Jiang, L. and Roth, J. R.: "Real Plasma Effects of Microwave Radiation Propagating Perpendicular to a Magnetized Plasma", Proceedings of the 1989 IEEE International Conference on Plasma Science, May 22-24, 1988, Buffalo, NY (1988).

Microwave absorbtion near electron cyclotron resonance has been investigated in a magnetized plasma over a wide range of frequencies, from 2 to 18 GHz. We have used a Hewlett Packard 8510 network analyzer, which is capable of swept frequency measurements, and of measuring reflection and transmission coefficients over these frequencies with 80 dB dynamic range. In previous work[1], a microwave beam was made to propagate along the axis of a magnetic mirror field. This radiation in the plasma column was attenuated up to 20 dB as it propagated along the axis of the magnetic mirror field at frequencies between 4 and 10 GHz[1]. This result suggests the feasibility of making targets disappear from radar screens by absorbing radar pulses in a magnetized plasma.

New experimental investigations have been undertaken on the attenuation of a microwave beam propagating across a uniform magnetic field with extraordinary and ordinary modes. The experimentally measured level of attenuation, absorption peak half-width, and phase angle are compared with the predictions of the Appleton equation[2].

The classical Penning discharge used to generate the plasma consists of a uniform magnetic field with a maximum value of 0.195T. An approximately 12 cm diameter and 118 cm long steady state plasma column is generated with a characteristic density of a few times 10^9 electrons/cm^3, and electron kinetic temperatures of a few tens of electron volts. Axial and radial Langmuir probes are used to measure electron number density and kinetic temperature.

1. L. Jiang and J. R. Roth, "Experimental Results of Microwave Absorption with Varying Magnetic Field in a Modified Penning Discharge", APS Bulletin, Vol. 25, No. 27, p. 1900, (1988).

2. M. A. Heald and C. B. Wharton, Plasma Diagnostics with Microwaves, (1978) New York.

*Supported by AFOSR contract 86-0100 (Roth)

Plasma Heating by Collisional Magnetic Pumping in a Steady-State Modified Penning Discharge*

Min Wu and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

This paper describes the experimental application of collisional magnetic pumping to heat a plasma by a sawtooth magnetic perturbation[1], and provides new results relating to the energy transfer process between the perturbed magnetic field and the parallel and perpendicular energy components of the heated species in a steady-state modified Penning discharge apparatus with a magnetic mirror configuration.

The general equation relating the change in total energy of a particle to the change of the magnetic field is

$$\frac{d^2E}{dt^2} - \frac{3}{2}\nu - \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\frac{dE}{dt} - \frac{\nu}{B}\frac{dB}{dt}E = 0$$

Using Floquet's theory and a perturbation treatment, Burger[2] et al. derived the energy increase rate when a sinusoidal perturbation is applied. The energy increase rate (or heating rate) is

$$\frac{dE}{dt} = \frac{\delta^2}{6}\,\frac{\nu\,\omega^2}{\frac{9}{4}\nu^2 + \omega^2}\,E,$$

In later work,[3] it was found that a sawtooth perturbation satisfies the condition for first order (in δ) heating, and the heating rate for this case (sawtooth) is

$$\frac{dE}{dt} = \frac{\delta\omega}{3\pi}E$$

This can be an improvement of two or three orders of magnitude on the sinusoidal case. Small values of δ are also easier to achieve experimentally.

Experimental data, including such plasma characteristics as P, T_e, T_i, n_e and type of gas will be discussed, and heating of ions and electrons as functions of magnetic induction, electron number density, and neutral gas pressure will be presented. The detailed design of the above apparatus will also be presented and discussed.

1. Min Wu, L. Jiang and J. R. Roth, "Experimental Results on Collisional Magnetic Pumping in a Modified Penning Discharge with Magnetic Mirror Configuration", APS Bulletin Vol. 33, No. 9, p2019 (1988).

2. J. M. Berger, et al., "Heating of a Confined Plasma by Oscillating Electromagnetic Fields", Phys Fluids, Vol. 1, No. 4, pp 301-307, (1958).

3. M. Laroussi and J. R. Roth, "Analytical, Computational, and Experimental Results on Plasma Heating by Collisional Magnetic Pumping", APS Bulletin 32, No. 9, p. 1950, (1987).

*Supported by AFOSR contract 86-0100 (Roth)

Wu, M. and Roth, J. R.: "Plasma Heating by Collisional Magnetic Pumping in a Steady-State Modified Penning Discharge", Proceedings of the 1989 IEEE International Conference on Plasma Science, May 22-24, 1988, Buffalo, NY (1988).

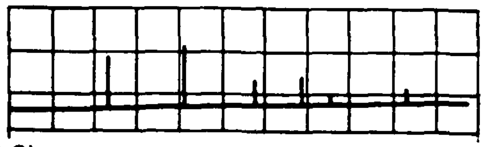
Steady-State, Gas-Filled Orbitron Maser

Mark Rader, Fred Dyer, and Igor Alexeff*

The University of Tennessee

The Gas-Filled Orbitron Maser[1,2] operates reliably in the steady-state. The output consists of narrow lines that do not shift in frequency as the discharge current is varied. A typical spectrum of the microwave emission is shown below.

TYPICAL HIGH FREQUENCY ORBITRON SPECTRUM



The primary reason that the device was previously operated in the pulsed mode was because the device was intended as a very-high-frequency source. Since the frequency scales as the square root of the applied voltage, and a gas-filled device cannot hold off voltages much over 1000 V, pulsed operation was used to obtain high transient voltages. However, steady-state operation is much more convenient for studying the physics of the device. The line spectrum emitted suggests that the alternate explanations of Orbitron operation as two interpenetrating electron beams involved in a beam-plasma interaction is not applicable here[3,4,5]. Our belief that particle orbits produce the radiation, and not three wave mixing, is also supported by the fact that we have observed a large potential drop between the anode and plasma thus indicating the presence of a large potential well.

*Work supported by the Airforce Office of Scientific Research. Contract #AFOSR-86-0100.

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2. V. Granatstein and I. Alexeff, High Power Microwave Sources, Artech House, p. 293, 1987.
3. R. W. Schumacher and R. J. Harvey, in 1984 IEEE Int. Conf. Plasma Science, Conf. Rec., p. 109.
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5. R. W. Schumacher, Bull. Amer. Phys. Soc., Vol. 29, p. 1601, Nov. 1986.

Rader, M.; Dyer, F. and Alexeff, I.: "Steady-State, Gas-Filled Orbitron Maser", Proceedings of the 1989 IEEE International Conference on Plasma Science, May 22-24, 1989, Buffalo, NY (1989).

A Visible Plasma

I. Alexeff, Fred Dyer and Mark Rader* _

University of Tennessee

We have obtained a steady-state plasma with the plasma frequency in the visible. Thus, in principle, phenomena such as the production of electron plasma oscillations can be observed visually. The plasma frequency is given by,

$$\omega_{pe} = \left(\frac{ne^2}{\varepsilon_0 m_e} \right)^{1/2},$$

here ω_{pe} is the plasma frequency (radians/second), e is the electron charge (1.6×10^{-19} coulomb), ε_0 is the permittivity of vacuum ($8.8? \times 10^{-12}$ farad/meter) and m_e is the electron mass ($.91 \times 10^{-30}$ kg). Our contribution is in noting that metallic cesium both has a very low value of free electron density, n, due to its bloated atomic size, and a large number of bound electrons (54) that are polarizable and increase the value of ε to 1.4165 ε_0. The low value of electron density alone results in a plasma frequency corresponding to light at 3630 Å (the ultra-violet), but adding in the correction to ε_0 results in a wavelength of 4320 Å, which is in the blue. We have succeeded in photographing the blue light penetrating above the cutoff at ω_{pe}. We note that R. W. Wood[1] states in his book, Physical Optics, that "The case of caesium is especially interesting as its region of high transparency begins in the visible violet, and films of the proper thickness transmit light of a rich violet color as deep and pure as that transmitted by a strong solution of cuprammonium or dense cobalt glass". Wood finds an experimental cutoff frequency of 4400 Å, but does not correlate this number with plasma effects. Further applications will be discussed.

*Work supported by Air Force Office of Scientific Research. Contract #AFOSR-86-0100.

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Alexeff, I.; Dyer, F. and Rader, M.: "A Visible Plasma", Proceedings of the 1989 IEEE International Conference on Plasma Science, May 22-24, 1989, Buffalo, NY (1989)

APPENDIX H

Title Pages and Abstracts of Graduate Theses Completed with The Support of Contract AFOSR 86-0100

PLASMA HEATING BY COLLISIONAL MAGNETIC PUMPING

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Mounir Laroussi

June 1988

ACKNOWLEDGEMENTS

The author is deeply indebted to Professor J. Reece Roth for excellent working conditions, good advice, and financial support. He also extends his gratitude to the remaining members of his dissertation committee: Professor I. Alexeff, Professor M. O. Pace, Associate Professor D. Rosenberg, and Professor L. G. Christophorou.

Special thanks go to Associate Professor Henry C. Simpson for his help and good suggestions.

The author wishes to thank Roberta L. Campbell for typing the manuscript of this dissertation with infinite patience, and Jenny L. Craven for drafting the figures.

Special thanks go to his wife Nicole C. Laroussi for her support and her constant help in typing the early drafts.

Finally, the author wishes to express his unbounded appreciation to his parents for their relentless support and encouragement throughout his academic career.

This work was supported by the Air Force Office of Scientific Research under contract 86-0100 (Roth).

ABSTRACT

Collisional magnetic pumping as a plasma heating method is investigated theoretically, computationally, and experimentally. Improvement of the efficiency of this heating method is also achieved. The theoretical treatment yields solutions to the energy transfer equations. The solution is presented in the form of an energy increase rate, which gives quantitatively the amount of energy increase per RF driving cycle. The RF wave adds a small perturbation to the background steady state DC magnetic field that confines the plasma. Depending on the type of waveform used, the energy increase rate obtained can be of first or second order in the amplitude of the magnetic field perturbation.

Two waveforms are used in this work. The first is a sinewave with variable frequency and amplitude. The energy increase rate in this case is proportional to the second power of the magnitude of the perturbation. This yields a small amount of heating for small perturbations. The second waveform used is a sawtooth with adjustable frequency and amplitude. The energy increase rate in this case is proportional to the first power of the magnitude of the perturbation. This yields an improvement of several orders of magnitude over the previous case.

Two circuits have been implemented to study experimentally the effects of the above mentioned perturbations on a cylindrical plasma generated by a classical Penning discharge. The circuit generating the sinusoidal perturbation is a high-Q parallel resonant circuit with tunable resonance frequency. The circuit generating the sawtooth perturbation is a switch-mode configuration using state-of-the-art metal-oxide-semiconductor transistors

capable of switching on and off in few tens of nanoseconds and of handling high curents and voltages. The experimental heating data collected in both cases is presented and discussed.

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CONVERSION OF THE HP3577A NETWORK ANALYZER TO A SPECTRUM ANALYZER MODE OF OPERATION WITH LOW NOISE AND CROSS-TALK

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

John E. Crowley

March 1987

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10.	Mark Rader, Fred Dyer, and Igor Alexeff: "Steady-State Operation of the High Vacuum Orbitron Maser", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.	G-10
11.	Igor Alexeff, Fred Dyer, and Mark Rader: "Probing the Pulsed Orbitron Glow Discharge", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.	G-11
12.	Laroussi, M. and Roth, J. R.: "Collisional Magnetic Pumping", Paper 5T7, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, June 1-3, Arlington, VA p. 103 (1987).	G-12
13.	Roth, J. R.: "Theory of Plasma Ion Implantation for Hardening Metals", Paper 6Y6, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, June 1-3, Arlington, VA p. 123-24 (1987).	G-13
14.	Alexeff, I.; Dyer, F.; and Rader, M.: "Time Dependent Frequency Shift in the Orbitron Maser", Paper 1C6, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, pp. 8-9 June 1-3, Arlington, VA, (1987).	G-14
15.	Rader, M.; Alexeff, I.; and Dyer, F.: "Cross Sectional Number Density in the Pulsed Orbitron Maser", Paper 1C5, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, pp. 8-9 June 1-3, Arlington, VA, (1987).	G-15
16.	Laroussi, M. and Roth, J. R.: "Analytical, Computational, and Exerimental Results on Plasma Heating by Collisional Magnetic Pumping", APS Bulletin, Vol. 32, No. 9 (1987) p. 1950.	G-16
17.	Rader, M.; Dyer, F.; and Alexeff, I.: "Average and Cross Sectional Number Densities in the Orbitron Maser", APS Bulletin, Vol. 32, No. 9 (1987) p. 1714.	G-17
18.	Dyer, F.; Rader, M.; and Alexeff, I.: "Upward Frequency Shifts with Declining Anode Voltage in the Orbitron Maser", APS Bulletin, Vol. 32, no. 9 (1987) p. 1714	G-18

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APPENDIX G

Abstracts of Oral and Poster Conference Presentations Supported by Contract AFOSR 86-0100

Igor Alexeff and J. Reece Roth, "A Simple MHD Model for Confinement Time Scaling in Tokamaks" Paper 2Q4, Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986) p. 38. ....

A Simple MHD Model for Confinement Time Scaling in Tokamaks*

Igor Alexeff and J. Reece Roth

Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

Experiments have demonstrated that the energy confinement time τ in tokamaks does not follow the classical scaling law prediction, $\tau \sim B^2/n$. We have developed a very simple scaling law based on MHD theory that predicts a confinement time scaling $\tau = Ca^2 T^{3/2}$, where T is the electron kinetic temperature, and a the plasma radius. The physical basis of this expression is the magnetic diffusivity of finite resistivity current filaments across the magnetic field.

The constant C in the above expression can be evaluated in two ways, both of which give similar values consistent with experiment. In one approach, we assume that a diamagnetic current impedes plasma expansion, and use Spitzer's expression for the resistivity appropriate to current flowing across the magnetic field.[1] In the second approach, we use the current along magnetic field lines which have a rotational transform. In this case, we use Spitzer resistivity along the field, which is lower, but note that the corresponding path length is longer and compensates. Our calculated confinement times account for the radial kinetic temperature (and conductivity) profile, and are longer (by a factor of 2-5) than quoted experimental energy containment times. Our scaling law was compared with a set of PLT measurements[2] (which included the $T_e(r)$ profile). Our scaling law gave confinement times a factor of 3 longer than the energy containment time measured.[2]

Our confinement time can be regarded as the skin depth penetration time for diamagnetic currents which balance the kinetic pressure of the plasma. The Bohr-van Leeuwen theorem states that a plasma will evolve through the operation of the second law of thermodynamics to a state of local classical kinetic equilibrium in which the diamagnetic currents are zero.[3,4] Our confinement time provides a measure of the time constant with which a plasma achieves this state of zero net diamagnetism.

*This work was supported by the Air Force Office of Scientific Research under contracts AFOSR-82-0ᐟ (Alexeff) and AFOSR 81-0093 (Roth).

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Mounir Laroussi and J. Reece Roth, "Plasma Heating by Collisional Magnetic Pumping", Paper 5D6, Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986) pp. 91-92.

Plasma Heating by Collisional Magnetic Pumping*

Mounir Laroussi and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

Collisional magnetic pumping[1] is achieved by wrapping an exciter coil around a cylindrical plasma and perturbing the confining magnetic field, $B = B_0(1 + \delta f(t))$, where f(t) is a bounded periodic function with a frequency below the ion cyclotron frequency. The transfer of energy between the perpendicular and parallel components of the ion velocity occurs through collisions. The change in the energy of the particles is governed by the following homogeneous linear differential equation with periodic coefficients,

$$\frac{d^2E}{dt^2} + \left[\frac{3}{2}\nu_c - \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right]\frac{dE}{dt} - \frac{\nu_c}{B}\frac{dB}{dt}E = 0$$

The above equation has been solved using Floquet's theory[2] along with a perturbation treatment. For the particular case where $f(t) = \cos \omega t$, the energy increase rate calculated[3] agrees with the one found by Berger et al.[4] The general case where f(t) is an arbitrary periodic function has been treated and a condition for a heating rate proportional to the first order of the field modulation $\delta = \Delta B/B_0$ is obtained. In this case we have

$$\frac{dE}{dt} = \delta\lambda_1 E_0$$

where

$$\lambda_1 = \frac{\nu_c}{T}\int_0^T e^{\frac{3}{2}\nu_c s}\left\{\frac{1}{1-\mathrm{Exp}\left(-\frac{3}{2}\nu_c T\right)}\int_0^T e^{-\frac{3}{2}\nu_c u} f'(u)\,du - \int_0^s e^{-\frac{3}{2}\nu_c u} f'(u)\,du\right\} ds$$

First order heating is possible because of the nonlinear relationship between the magnetic field and the energy increase rate. With a perturbation that keeps the magnetic moment under the exciter coil always larger than the background value, the net stochastic energy flow is unidirectional into parallel energy components.

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*Supported by AFOSR contract 81-0093 (Roth)

3C4

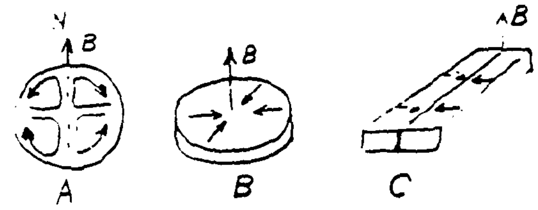
AN IMPROVED MHD MODEL FOR THE EARTH'S MAGNETIC FIELD*

Igor Alexeff and J. Reece Roth

University of Tennessee

A large literature exists concerning the origin of the Earth's magnetic field via a thermally-driven MHD generator.(1) The universal opinion is that a symmetric flow pattern cannot support a steady-state field. In this paper, we demonstrate that a symmetric flow can support a steady-state magnetic field, if the electrical conductivity of the magma is allowed to vary as a function of temperature. This is equivalent to variation as a function of radius in a planetary interior.

As a first assumption, we model the Earth's core as composed of two convection cells, as shown below in A. However, the return path flows over the surface of the



planet, where the temperature and conductivity is lower. Thus, the MHD effect of the return path can be to first order neglected. Our equivalent path is shown in B. For ease of computation, a slab model is shown in C.

The differential equation governing the flow is,

$$\frac{1}{\mu_0\sigma}\;\frac{\partial^2 B_z}{\partial y^2} + 2v_0 B_z \delta(y) + v_0\,\frac{\partial B_z}{\partial y}\,\text{signum}(y) = \frac{\partial B_z}{\partial t}\;.$$

The first term is the standard diffusion term. The third term is Alfven's convection term. The second term is our new term, which corresponds to a source at the center.

The steady-state solution of this differential equation is, on the right half plane,

$$B_z = B_0 e^{-(v_0\sigma\mu_0)y} + B_1$$

which produces a steady-state narrow peak on axis. Use of known values of the core conductivity and flow rate produce a peak for B having a half-width about 10 km broad.

(1) For example, H.K. Moffatt, "Magnetic Field Generation in Electrically Conducting Fluids", Cambridge University Press, 1978.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-82-0045 (Alexeff) and office of Naval Research contract ONR N00014-80-C-0063 (Roth). (A preliminary version of this work was presented at this conference last year).

Igor Alexeff and J. Reece Roth, "An Improved MHD Model for the Earth's Magnetic Field", Paper 3C4, Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986) p. 48.

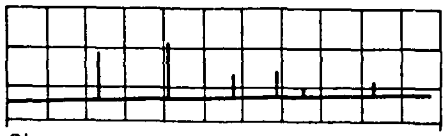
Steady-State, High-Vacuum Operation of the Orbitron Maser.*

Mark Rader, Fred Dyer, and Igor Alexeff
University of Tennessee 37996-2100

We have operated our Orbitron Maser[1] in a high vacuum of 2 x 10^{-6} torr produced by an oil diffusion pump trapped by a liquid-nitrogen-cooled baffle. Electrons are supplied by an oxide-coated tungsten hot cathode placed inside the cylindrical cavity. To demonstrate that no plasma was present to produce plasma oscillations, as claimed by Schumacher and Harvey[2,3] we monitored the presence of plasma in the open cavity. The plasma-free emission corresponded to harmonically-related, steady-state, narrow lines. The fundamental (lowest frequency) line corresponded to a resonance in the cavity system, which could be observed with a grid-dip meter. The highest frequency line corresponded to 10GHz, which is about the frequency of an electron just grazing the wire in a circular orbit at the voltage used (600 volts).

To obtain these results, we use multiple anode wires (up to 7) to increase the space-charge limited current. Apparently, mode-locking between electrons on adjacent wires occurs. We have also been able to frequency-tune (pull) the resonant lines by adjusting anode voltage. Finally, we have suppressed the lower-frequency lines by excluding large-orbit electrons from the device.

TYPICAL HIGH FREQUENCY ORBITRON SPECTRUM



In our pulsed gas-filled tubes, a much higher voltage can be used, as well as a thinner wire. In this mode of operation, sub-millimeter operation is routine, and we have obtained radiation[4] at 1 THz (0.3mm). Peak microwave power output is about 1.5 watts at 1 THz and about 50 watts at frequencies up to 100 GHz. Efficiency ranges from 10% at 3.5 GHz to 1 x 10^{-3}% at 1 THz.

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*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-82-0045-Alexeff.

Mark Rader, Fred Dyer, and Igor Alexeff, "Steady-State, High Vacuum Operation of the Orbitron maser", Paper 4E8, Proceedings of the 1986 International Conference on Plasma Science, May 19-21, 1986, Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986), p. 81.

5R REVIEW PAPER

Basic Plasma Science and High Power Microwave Generation.

I. Alexeff, Univ. of Tenn., Knoxville, TN.

Invited Review Paper: Igor Alexeff, "Basic Plasma Science and High Power Microwave Generation", Paper 5R, Proceedings of the 1986, International Conference on Plasma Science, May 19-21, 1986,Saskatoon, Canada IEEE Catalog No. 86CH2317-6, (1986), p. 81.

Application of Magnetic Pumping to a Classical Penning Discharge*. MOUNIR LAROUSSI, and J. REECE ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville, TN 37996-2100 -- The Classical Penning discharge consists of a straight cylindrical plasma with a constant axial magnetic field. Magnetic pumping is achieved by wrapping an exciter coil of length L around the plasma. The confining magnetic field is then perturbed, $B = B_o(1 + \delta f(t))$, where f(t) is a periodic function. The differential equation describing the exchange of energy is

$$\frac{d^2E}{dt^2} + \left[\frac{3}{2}v_c - \frac{d^2B}{dt^2}\left(\frac{dB}{dt}\right)^{-1}\right]\frac{dE}{dt} - \frac{v_c}{B}\frac{dB}{dt}E = O.$$

The above equation has been solved for two forms of the perturbing function f(t). For a sine-wave[1], the energy increase rate is proportional to δ^2. For a sawtooth[2], it is proportional to δ, and much larger in magnitude. A computer simulation was applied to yield the behavior of the energy components with time. A high Q parallel resonant circuit has been designed to generate the RF perturbed magnetic field.

(1) J. M. Berger, et al.: Physics of Fluids, Vol. 1, (1958) pp. 301-307.

(2) M. Laroussi, Proc. SSST, (1986), p. 475-480, IEEE ISSN 0094-2898.

*Supported by AFOSR contract 86-0100 (Roth)

Mounir Laroussi and J. Reece Roth: "Application of Magnetic Pumping to a Classical Penning Discharge", APS Bulletin, Vol. 31, No. 9, (1986), p. 1421.

Two-Channel, Low Cross-Talk Diagnostic System for Measuring Nonlinear Mode Coupling in a Turbulent Plasma*. JOHN E. CROWLEY and J. REECE ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville, Tennessee 37996-2100 -- A system has been designed which modifies the HP 3577A Network Anayzer so that arbitrary signals in the range from 500 kHz to 10 MHz can be compared in amplitude and phase. The system will be used to sample density or potential fluctuations at two points in a turbulent plasma, and measure the frequency, amplitude, and phase of signals detected by the probes. This modification is totally external to the HP 3577A Network Analyzer, and has been designed to minimize the cross-talk between the two channels, so that nonlinear mode coupling processes in the plasma can be distinguished from mode coupling (cross-talk) originating within the instrumentation itself. The composite system should have a dynamic range from 0 dBm to -80 dBm, cross-talk no more than -60 dB between channels, a maximum spurious response - 50 dB below the maximum input signal, and an amplitude and phase accuracy of 1 dB and 5 degrees, respectively.

*Supported by Contract AFOSR 86-0100 (ROTH).

John E. Crowley and J. Reece Roth: "Two-Channel, Low Cross-Talk Diagnostic System for Measuring Nonlinear Mode Coupling in a Turbulent Plasma" APS Bulletin, Vol. 31, No. 9 (1986) p. 1596.

Characterization of a Steady-State, Classical Penning Discharge*. J. E. BREEDING, M. E. IRWIN, A. KESHAVARZI, D. L. SAFFER, M. LAROUSSI, and J. R. ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville, TN 37996-2100. -- Our classical Penning discharge is operated in the steady state, and produces an approximately axially uniform plasma 80 cm long and 10 cm in diameter in a constant magnetic induction up to 0.4 T. This plasma is electric field dominated, with axial and radial electric fields up to several hundred volts per centimeter; exhibits E/B and grad B drift waves; is highly turbulent; emits broadband RF emission at the fundamental and harmonics of the geometric mean emission frequency, and at the electron plasma frequency; has number densities from 10^9 to $10^{11}/cm^3$; electron kinetic temperatures of a few tens of eV, and ion energies up to several keV. In this paper we report data on the continuity-equation oscillation in this plasma; statistical properties of its plasma turbulence; radial and axial profiles of the ion and electron kinetic temperatures, number density, and plasma potential; and the nature of the ion energy distribution function, as it is affected by the plasma operating conditions.

*Supported by contract AFOSR 86-0100 (ROTH).

J. E. Breeding, M. E. Irwin, A. Keshavarzi, D. L. Shaffer, M. Laroussi, and J. R. Roth: "Characteristization of a Steady-State, Classical Penning Discharge", APS Bulletin, Vol. 31, No. 9 (1986) p. 1579.

Constant Frequency Plasma Oscillations*, FRED DYER, MARK RADER, and IGOR ALEXEFF, University of Tennessee 37996-2100 -- We have been observing a new and previously undetected steady-state spectral line being emitted from a device with the same basic design as our pulsed orbitron maser.[1] Upon investigation of these spectral lines we found that the fundamental (lowest frequency) line was the stable steady-state emission of the electron plasma frequency (ω_p). We believe that this frequency stability is caused by the continual flushing of ions from the system and their subsequent replacement by new ions. This flushing damps the instabilities, which cause the frequency drift seen in other ion plasma oscillators, before they form.

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980); I. Alexeff, Phys. Fluids, 28, 1990, June 1985.

*Work supported by the Air Force Office of Scientific Research under grant AFOSR-86-0100.

Fred Dyer, Mark Rader, and Igor Alexeff: "Constant Frequency Plasma Oscillations", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.

Steady-State Operation of the High Vacuum Orbitron Maser*, MARK RADER, FRED DYER, and IGOR ALEXEFF, University of Tennessee 37996-2100 -- We have operated our radial injection orbitron at a pressure of 1 x 10^{-6} torr[1]. Electrons are supplied to this system by means of an axial, oxide-coated hot tungsten filament. The plasma-free emission of this device corresponded to harmonically-related, steady-state, narrow lines unlike the results obtained by others[2]. Depending upon the device's design, the fundamental (lowest frequency) line corresponded either to a external resonance, or to a TEM cavity mode. Operation of these devices is routine in the 0 - 2 GHz frequency range. Frequencies as high as 1.5 GHz have been observed at the low operating voltage of 40 volts. To obtain these results, we have used multiple anode wires (up to 7) to increase the space-charge limited current, and apparent mode-locking between electrons orbiting adjacent wires occurs.

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980); I. Alexeff, Phys. Fluids, 28, 1990, June 1985.
2. R. W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October, 1984.

*Work supported by the Air Force Office of Scientific Research under grant AFOSR-86-0100.

Mark Rader, Fred Dyer, and Igor Alexeff: "Steady-State Operation of the High Vacuum Orbitron Maser", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.

Probing the Pulsed Orbitron Glow Discharge*, IGOR ALEXEFF, FRED DYER, and MARK RADER, University of Tennessee 37996-2100 -- To study the suggestion that the pulsed Orbitron emission[1] is due to plasma oscillations[2], we have probed the plasma with a microwave signal from an external oscillator. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a wavelength of 4 mm or shorter, with a penetrating beam at 9 mm. This suggests that under specific conditions, plasma oscillations are not the emission mechanism. Similar conclusions have been obtained by using both passive optical probing, and a Langmuir Probe.

1 I. Alexeff. Phys. Fluids, 28, 1990, June 1985.

2. R. W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October, 1984: R. W. Schumacher and R. J. Harvey, 1984 IEEE International Conference on Plasma Science, Conference Record, P. 109, IEEE Publication No. 84ch 1958-8.

*Work supported by the Air Force Office of Scientific Research under grant AFOSR-86-0100.

Igor Alexeff, Fred Dyer, and Mark Rader: "Probing the Pulsed Orbitron Glow Discharge", APS Bulletin, Vol. 31, No. 9 (1986) p. 1603.

5T7 Collisional Magnetic Pumping*

Mounir Laroussi and J. Reece Roth
UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, TN 37996-2100

ABSTRACT

This paper describes the application of collisional magnetic pumping[1,2] to heat a plasma, and provides new results relating to the energy transfer process between the RF perturbed magnetic field and the parallel and perpendicular energy components of the heated species. From numerical solutions to the energy transfer problem, it has been found that there exists a plasma parameter regime in which collisional magnetic pumping is most effective, and for each collision frequency ν_c there exists an optimum driving frequency ν which maximizes the energy transfer from the perpendicular component of the ion and electron motion to the parallel components. It has also been found that there exists a threshold in the parameter $\nu_c T$, where T is the period of the driving frequency, below which the parallel component of the energy saturates after an initial transient phase, and the collisional magnetic pumping is no longer effective. The heating rates for different forms of the perturbing function f(t), including a sawtooth and a triangular function, have been found theoretically[3] and compared to that of other selected RF heating methods including ICRH and ECRH.

The high Q parallel resonant circuit required to generate the broadband RF perturbed field will be described along with the experimental results on the power absorption. The experiment is performed on a classical Penning discharge with an axially uniform, steady state magnetic field. This field is RF perturbed by wrapping an exciter coil of length L around the plasma. The magnetic field under the coil assumes the form $B = B_0\,(1+\delta\, f(t))$ where B_0 is the background static field, δ the field modulation and f(t) the perturbing function. The heating rate is plotted against various plasma parameters and its dependence on the field modulation is established.

1. J. M. Berger, *et. al.*: Physics of Fluids, Vol. 1, No. 4 (1958) pp. 301-307.
2. M. Laroussi, "Plasma Heating by Collisional Magnetic Pumping". 18th Southeastern Symposium on System Theory, April 7-8, 1986.
3. M. Laroussi and J. Reece Roth, "Application of Magnetic Pumping to a Classical Penning Discharge". APS Bulletin, Vol. 31, No. 9, p. 1421, (1986).

*Supported by AFOSR contract 86-0100 (Roth)

Laroussi, M. and Roth, J. R.: "Collisional Magnetic Pumping", Paper 5T7, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, June 1-3, Arlington, VA p. 103 (1987).

THEORY OF PLASMA ION IMPLANTATION FOR HARDENING METALS*

Prof. J. Reece Roth
UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

ABSTRACT

A problem with existing methods of hardening metals by ion implantation is that the ion beams normally used do not lend themselves to implanting the ions uniformly on complex surfaces such as gear teeth, screw threads, turbine blades, etc. If one inserts a metallic sample into a plasma and biases it negatively, deep into the ion saturation region as though it were a Langmuir probe, the surface of the sample will be isotropically bombarded by ions over scale sizes larger than the local Debye length. If the sample is biased to negative potentials of 50 kV or more, useful amounts of ion implantation can occur in very short times in samples such as spheres and gear teeth[1,2]. Ion energies of about 50 keV normally lead to implantation depths of a tenth of a micron or so at room temperature, but it seems that ions implanted at these energies manage to migrate ahead of the wear surface and maintain surface hardness even after several tenths of a micron of surface material are worn away[2].

This paper examines the plasma parameters required to achieve a given level of ion implantation in complex metal objects, how to calculate exposure times, energy requirements, and other commercially significant factors in the application of this new process. It is shown that the surface fluxes of 50 keV ions from plasma ion implantation can exceed those from space charge limited ion beam sources; that relatively modest and easily generated steady-state plasmas can isotropically bombard samples with a Debye length and scale size of less than 0.5 mm; that an exposure time of only a few seconds is required to produce useful levels of ion implantation; that the power delivered to the sample can be made much smaller than the level required to melt it; that by pulsing the high negative biasing voltage on and off with an appropriate duty cycle, the ions required for implantation on a sample of several tens of square centimeters will not significantly deplete a relatively modest plasma; and that the total power and energy required to achieve a given level of hardness by plasma ion implantation is far below that required by conventional foundry techniques.

1. J. Bell, R. Herman, and C. Sutton, New Scientist, March 6, 1986, pp. 34-36.
2. Private communication, Dr. John R. Conrad, Univ. of Wisconsin, August, 1986.

*Supported in part by ONR contract N00014-80-C-0063 and by contract AFOSR 86-0100 (Roth).

Roth, J. R.: "Theory of Plasma Ion Implantation for Hardening Metals", Paper 6Y6, Proceedings of the 1987 IEEE International Conference on Plasma Science, June 1-3, 1987, Alington, VA, IEEE Catalog #87CH2451-3 (1987) pp. 123-24.

1C6

TIME DEPENDENT FREQUENCY SHIFT IN THE ORBITRON MASER* Igor Alexeff, Fred Dyer, Mark Rader, University of Tennessee 37996-2100:

It has been observed by both ourselves and others[1], that the frequency output in our pulsed Orbitron maser chirps upward in time as the discharge voltage declines. This is explained by the way the Orbitron operates. The Orbitron maser[2] is a device in which electrons orbit a positively charged central wire placed on axis in a cavity resonator. The rotating electrons couple to microwave cavity modes and generate RF radiation. These electrons are born on the outer edge of the cavity-wire system and drift inward. Since the frequency output of the electron is inversely proportional to the electron radius in the system, and the electron cloud must move inward into the potential well to obtain the work required for microwave emission, one would expect to see a shift upward in frequency as the pulse progresses even though the potential well is collapsing.

We have predicted this upward frequency chirp from the basic theory of this device and have found it to be in good agreement with what we experimentally observe. Using standard charcteristics of these devices, the chirp rate has been found to be 3.55×10^{17} Hertz per second, and in a characteristic experiment, using a device of the same dimensions as was used in our calculations, we get a chirp rate of 5.5×10^{17} Hertz per second.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

1. R.W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October, 1984: R. W. Schumacher and R. J. Harvey, 1984 IEEE Internatoinal Conference on Plasma Science, Conference Record, P 109, IEEE Publication No 84ch 1958-8: Private conversation with R. W. Schumacher.
2. I. Alexeff, Phys. Fluids, 28, 1990, June 1985.

Alexeff, I.; Dyer, F.; and Rader, M.: "Time Dependent Frequency Shift in the Orbitron Maser", Paper 1C6, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, pp. 8-9 June 1-3, Arlington, VA, (1987).

1C5

CROSS SECTIONAL NUMBER DENSITY IN THE PULSED ORBITRON MASER* Mark Rader, Igor Alexeff and Fred Dyer, University of Tennessee 37996-2100

To study the suggestion that the pulsed Orbitron emission[1] is due to plasma oscillations[2], we have probed the plasma with a microwave signal from an external oscillator. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a frequency of 133 GHz or higher, with a penetrating beam at 36 GHz. This gives a emission to bulk plasma frequency ratio of 3.7 to 1. We have also used a radially adjustable Langmuir Probe to study the electron number density at points across the discharge radius. The peak electron plasma frequency in this device at a radius of 40 mils (1 mm) was found to be about 10.6 GHz. The peak frequency emitted by this device was found to be 38 GHz. This gives a peak emission to peak plasma frequency ratio of 3.6 to 1. The peak number density occurs between .5 to 1 microseconds after the peak emission occures.

The electron temperature at this point was about 25 eV with a plasma potential (V_p) of 150 V. Since the Orbitron maser is a coaxial system with a positively charged wire at the center, 10 kV in this case, this plasma potential indicates a potential well for electron trapping.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100

1. 1. Alexeff, Phys. Fluids, 28, 1990, June 1985.
2. R. W. Schumacher and R. J. Harvey, Bull. A.P."S., 29, 1179, October, 1984: R. W. Schumacher and R. J. Harvey, 1984 IEEE International Conference on Plasma Science, Conference Record, P 109, IEEE Publication No 84ch 1958-8.

Rader, M.; Alexeff, I.; and Dyer, F.: "Cross Sectional Number Density in the Pulsed Orbitron Maser", Paper 1C5, Conference Record IEEE 87CH2451-3, 1987 IEEE International Conference on Plasma Science, pp. 8-9 June 1-3, Arlington, VA, (1987).

9R 18 Analytical, Computational, and Experimental Results on Plasma Heating by Collisional Magnetic Pumping*. MOUNIR LAROUSSI and J. REECE ROTH, Plasma Science Laboratory, University of Tennessee, Knoxville, TN 37996-2100 -- The equations describing the energy transfer between the RF field and the charged particles due to collisional magnetic pumping[1] are solved analytically and numerically for different RF magnetic field waveforms.[2] The results are then compared and an optimum working regime is found. If a sinewave perturbation is used with a field modulation factor of 10% and an initial particle energy of 10ev, which is typical of electrons in our plasma, the maximum energy increase is found to be about 3 10^{-2} ev per RF cycle. In the case of a sawtooth perturbation, the heating rate is found to be proportional to the first order of the field modulation factor, and the energy increase for the above conditions is about 67 10^{-2} ev per RF cycle. The experimental setups for both sinewave and sawtooth perturbation will be discussed along with the energy absorption measurement and a theory-experiment comparison.

*Supported by contract AFOSR 86-0100 (Roth).

1. J. M. Berger, et al., Physics of Fluids, Vol. 1, (1958), pp. 301-307.
2. M. Laroussi, and J. R. Roth, 14th IEEE Int. Conf. on Plasma Science, IEEE No. 87CH2451-3 (1987), p. 103.

Laroussi, M. and Roth, J. R.: "Analytical, Computational, and Exerimental Results on Plasma Heating by Collisional Magnetic Pumping", APS Bulletin, Vol. 32, No. 9 (1987) p. 1950.

1E 9 Average and Cross Sectional Number Densities in the Orbitron Maser*, Mark Rader, Fred Dyer, and Igor Alexeff, University of Tennessee, 37996-2100:
In order to better understand the pulsed glow Orbitron MASER, we have been using a penetrating microwave beam to make bulk measurement of the number density in the plasma. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a frequeny of 250 GHz or higher, while a microwave beam at 37.5 GHz was penetrating the glow discharge. This gives a emission to bulk plasma frequency ratio of 6.7 to 1. We have also used a radially inserted Langmuir probe to measure both the electron number density across the plasma chord and the electron temperature. From this probe we found the peak electron plasma frequency in this device at a distance of 40 mils (1 mm) from the central wire was about 10.6 GHz. The peak frequency emitted by this device was found to be 38 GHz. This gives a peak emission to peak plasma frequency ratio of 3.6 to 1. These and other experimental results lead us to conclude that the emitted frequency is apparently not related to the electron plasma frequency.
*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

Rader, M.; Dyer, F.; and Alexeff, I.: "Average and Cross Sectional Number Densities in the Orbitron Maser", APS Bulletin, Vol. 32, No. 9 (1987) p. 1714.

IE 10

Upward Frequency Shifts with Declining Anode Voltage in the Orbitron MASER* Fred Dyer, Mark Rader, and Igor Alexeff, University of Tennessee 37996-2100:

It has been observed that the frequency output in our pulsed Orbitron MASER chipra upward in time even though the anode voltage is decreasing. This can be explained by the physics of the Orbitron MASER. The Orbitron MASER[1] is a device in which electrons orbit a positively charged central wire placed on axis in a cavity resonator. The rotating electrons couple to microwave cavity modes and generate RF radiation. These electrons are born on the outer edges of the cavity-wire system and spiral inwards. In this device the frequency output of the electrons is inversely proportional to the electron radius in the system, and is only related to the square root of the difference in potential between the anode and cavity wall. Since the electrons spiral inward during each pulse, one would expect to see a shift upward in frequency as the pulse progresses even though the potential well is collapsing. We have predicted this upward frequency chirp from the basic theory of this device and have found it to be in good agreement with what we experimentally observe. Using standard characteristics of these devices the chirp rate has been found to be 3.55×10^{17} Hertz per second, and in a characteristic experiment, using a device of the same dimensions as was used in our calculations, we get a chirp rate of 5.5×10^{17} Hertz per second.

*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

1. I. Alexeff, Phys. Fluids, 28, 1990, June 1985.

Dyer, F.; Rader, M.; and Alexeff, I.: "Upward Frequency Shifts with Declining Anode Voltage in the Orbitron Maser", APS Bulletin, Vol. 32, no. 9 (1987) p. 1714 .

Laroussi, M. and Roth, J. R.; "Latest Experimental Results on the Application of Collisional Magnetic Pumping to Heat a Steady-State Plasma", Paper 1P2, Proceedings of the 1988 IEEE International Conference on Plasma Science, June 6-8, 1988, Seattle, Washington, IEEE Catalog No. 88CH2559-3 (1988) p. 36.

1P2

Latest Experimental Results on the Application of Collisional Magnetic Pumping to Heat a Steady State Plasma*

Mounir Laroussi and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

In previous work[1] we showed that collisional magnetic pumping[2] can be an efficient way to heat a plasma if the right magnetic field perturbation is used. A sinewave perturbation proved to achieve second order heating[1,2]. A sawtooth perturbation causes first order heating for small field modulation factors[1]. This proved to have an energy increase rate two to three orders of magnitude larger than the previous case.

An experimental attempt to observe heating is under progress. For this, two different apparatus have been designed, built, and tested. The first is a high-Q tunable parallel resonant circuit capable of generating a sinusoidal RF magnetic field. When applied to the plasma, this field adds an RF perturbation to the background DC magnetic field. The diagnostics used to probe the change in the energy of the particles due to collisional magnetic pumping are a Langmuir probe to measure the electron and ion temperature, a retarding potential analyser to monitor the particles energy distribution, and a network analyser to sense impedance changes due to energy absorption.

The second apparatus is a switching circuit capable of driving a current sawtooth through the exciter coil, which in turn generates a sawtooth magnetic field perturbation superimposed on the background magnetic field. The switch used is a TMOS (Metal-Oxide-Semiconductor) transistor capable of switching on and off in few tens of nanoseconds, and of sustaining high currents at relatively high voltages. The energy of the particles is diagnosed as mentioned above.

The experimental data along with the detailed design of the above apparatus will be presented and discussed.

1. M. Laroussi and J. R. Roth, APS Bulletin, Vol. 32, No. 9. p. 1950, (1987).

2. J. M. Berger, et al., Physics of Fluids, Vol. 1, No. 4, pp. 301-307, (1958).

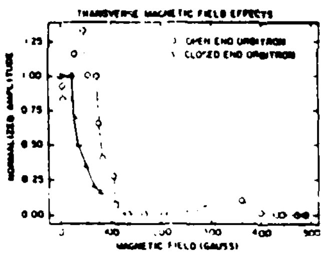
*Supported by AFOSR contract 86-0100(Roth).

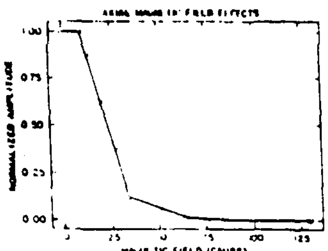
3C3

Magnetic Output Control, and External Frequency Control of the Orbitron MASER*

Igor Alexeff, Fred Dyer, and Mark Rader
University of Tennessee
Knoxville, TN 37996-2100

The Orbitron MASER is a negative mass unstable device in which electrons orbit a positively charged wire. It has a unique feature, in that no external magnetic field is required. We have been studying the effect an external magnetic field has on the RF output of this device. The effect was studied for two cases, one in which the field was parallel to the axis of electron rotation, and the other in which the field was perpendicular to this axis. The field, in all cases, was varied between 0 and at least 100 Gauss. We found that, for all cases, the use of a small (on the order of 20 Gauss) externally applied field reduced the RF output of the device and that there was no significant RF output at fields over 100 Gauss[1] for both cases, in contrast to the results of others[2]. The relative output verses magnetic field, for both cases, is shown below. The outer radius of this device was approximately 1 cm. We also found that the field required suppress the instability was inversely proportional to the radius of the outer cavity.





The power for this device is supplied by capacitor bank, which is switched by an adjustable spark gap. We have found that it is possible to control the output spectra of this device by varying the capacitance of this bank. By reducing this capacitance to the proper level, it is possible suppress the lower frequencies emitted, while leaving the higher frequencies relatively unchanged.

1. F. Dyer, I. Alexeff, H. F. Karimy, and W. Nakonieczny, 1984 IEEE International Conference On Plasma Science, Pg 109, IEEE Pub # 84CH1958-8
I. Alexeff, Bull. A.P.S. 26, #7, Pg 1046 October 1981

2. R. W. Schumacher and R. J. Harvey, 1984 IEEE Conference on Plasma Science, Pg 109 IEEE Pub # 84CH1958-8

* Work Supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100

Alexeff, I.; Dyer, F.; and Rader, M.: "Magnetic Output Control, and External Frequency Control of the Orbitron Maser", Paper 3C3, Proceedings of the 1988 IEEE International Conference on Plasma Science, June 6-8, 1988, Seattle, WA, IEEE Catalog No. 88CH2559-3 (1988) p. 72.

Experimental Results on Collisional Magnetic Pumping in a Modified Penning Discharge with Magnetic Mirror Configuration.* MIN WU, L. JIANG, and J. R. ROTH, University of Tennessee, Knoxville TN 37996-2100 -- This paper describes the application of collisional magnetic pumping to heat a plasma[1,2], and provides new results relating to the energy transfer process between the RF perturbed magnetic field and the parallel and perpendicular energy components of the heated species in a modified Penning discharge apparatus with a magnetic mirror configuration. A switching circuit capable of driving a current sawtooth through the exciter coil was developed, which generates a sawtooth magnetic field perturbation superimposed on the background DC magnetic field. The diagnostics used to probe the change in the energy of the particles due to collisional magnetic pumping are a Langmuir probe to measure the electron kinetic temperature, a retarding potential analyser to monitor the ion energy distribution, and a network analyser to sense impedance changes due to energy absorption. The experimental data along with the detailed design of the above apparatus will be presented and discussed.

*Supported by AFOSR contract 86-0100 (Roth).

1. M. Laroussi and J. R. Roth, APS Bulletin, Vol. 32, No. 9, p. 1950, (1987)
2. J. M. Berger, et al., Physics of Fluids, Vol. 1, No. 4, pp. 301-307, (1958).

Wu, M.; Jiang, L. and Roth, J. R.: "Experimental Results on Collisional Magnetic Pumping in a Modified Penning Discharge with Magnetic Mirror Configuration", APS Bulletin, Vol. 33, No. 9 (1988) pp 2019-20.

Experimental Results of Microwave Absorption with Varying Magnetic Field in A Modified Penning Discharge.* L. JIANG, MIN WU, and J. R. ROTH, University of Tennessee, Knoxville TN 37996-2100 -- Microwave absorption in a varying magnetic field is investigated near electron cyclotron resonance[1] with a Hewlett Packard 8510 Network Analyzer which is capable of swept frequency measurements, and of measuring reflection and transmission coefficients from 0.045 to 18 GHz, with greater than 80 dB dynamic range. The experimental conditions are such that the plasma is generated in a modified Penning discharge in a magnetic mirror configuration. A Langmuir probe is used to measure electron number density and kinetic temperature. A microwave beam is caused to propagate along the axis of the magnetic mirror field in the plasma column. The microwave beam is attenuated near the electron cyclotron reasonance frequency, in the range of a few GHz microwave absorbtion. The attenuation, along with hot-plasma effects, are measured as a function of frequency by the Hewlett Packard 8510 Network Analyzer.

*Supported by AFOSR Contract 86-0100(Roth)

1. M. A. Heald and C. B. Wharton, Plasma Diagnostics with Microwaves, (1978) New York.

Jiang, L.; Wu, M. and Roth, J. R.: "Experimental Results of Microwave Absorption with Varying Magnetic Field in a Modified Penning Discharge", APS Bulletin, Vol. 33, No. 9 (1988) pp 119.

Magnetic Output Control and Self-Damping of the Orbitron MASER* Igor Alexeff, Fred Dyer, and Mark Rader, University of Tennessee -- The Orbitron MASER is a negative mass unstable device which has a unique feature, in that no external magnetic field is required. The effect of an external magnetic field was studied for two cases, one in which the field was parallel to the axis of electron rotation, and the other in which the field was perpendicular to this axis. We found that the use of a small (on the order of 20 Gauss) externally applied field reduced the RF output of the device and that there was no significant RF output at fields over 100 Gauss for both cases. We have also done some theoretical calculations based on the experimental magnetic field data. In these calculations, we predict that the current in the device reaches a level to produce a magnetic field of sufficient amplitude to kill the instability. We have confirmed this experimentally.

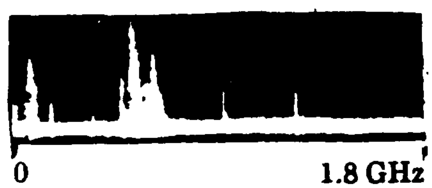
*Work Supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

Alexeff, I.; Dyer, F. and Rader, M.: "Magnetic Output Control and Self-Damping of the Orbitron MASER", APS Bulletin, Vol. 33, No. 9 (1988) pp 2008.

6F 8 Steady-State Operation of the Gas-Filled Orbitron Maser.* Mark Rader, Fred Dyer, James Carroll, and Igor Alexeff, The University of Tennessee. -- We have operated gas-filled, cold-cathode Orbitron Masers in the steady-state at low voltages (below 400 V) and low currents (below 40 mA). The emission spectrum consists of narrow lines that do not vary in frequency as the discharge pressure and current are changed. The highest frequency observed corresponds closely to that predicted from our simple orbit theory.[1] This suggests that the oscillations do not correspond to the plasma frequency, as claimed by others.[2]

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980).
2. R. W. Schumacher and R. J. Harvey, Bull. APS 29, 1179 (1984), and subsequently.

*Work supported by the Air Force Office of Scientific Research under grant #AF-AFOSR-86-0100.



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Real Plasma Effects of Microwave Radiation Propagating Perpendicular to a Magnetized Plasma*

Lili Jiang and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, TN 37996-2100

Microwave absorbtion near electron cyclotron resonance has been investigated in a magnetized plasma over a wide range of frequencies, from 2 to 18 GHz. We have used a Hewlett Packard 8510 network analyzer, which is capable of swept frequency measurements, and of measuring reflection and transmission coefficients over these frequencies with 80 dB dynamic range. In previous work[1], a microwave beam was made to propagate along the axis of a magnetic mirror field. This radiation in the plasma column was attenuated up to 20 dB as it propagated along the axis of the magnetic mirror field at frequencies between 4 and 10 GHz[1]. This result suggests the feasibility of making targets disappear from radar screens by absorbing radar pulses in a magnetized plasma.

New experimental investigations have been undertaken on the attenuation of a microwave beam propagating across a uniform magnetic field with extraordinary and ordinary modes. The experimentally measured level of attenuation, absorption peak half-width, and phase angle are compared with the predictions of the Appleton equation[2].

The classical Penning discharge used to generate the plasma consists of a uniform magnetic field with a maximum value of 0.195T. An approximately 12 cm diameter and 118 cm long steady state plasma column is generated with a characteristic density of a few times 10^9 electrons/cm^3, and electron kinetic temperatures of a few tens of electron volts. Axial and radial Langmuir probes are used to measure electron number density and kinetic temperature.

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2. M. A. Heald and C. B. Wharton, Plasma Diagnostics with Microwaves, (1978) New York.

*Supported by AFOSR contract 86-0100 (Roth)

Jiang, L. and Roth, J. R.: "Real Plasma Effects of Microwave Radiation Propagating Perpendicular to a Magnetized Plasma" Proceedings of the 1989 IEEE International Conference on Plasma Science, May 22-24, 1988, Buffalo, NY (1988).

Plasma Heating by Collisional Magnetic Pumping in a Steady-State Modified Penning Discharge*

Min Wu and J. Reece Roth

UTK Plasma Science Laboratory
Department of Electrical and Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100

This paper describes the experimental application of collisional magnetic pumping to heat a plasma by a sawtooth magnetic perturbation[1], and provides new results relating to the energy transfer process between the perturbed magnetic field and the parallel and perpendicular energy components of the heated species in a steady-state modified Penning discharge apparatus with a magnetic mirror configuration.

The general equation relating the change in total energy of a particle to the change of the magnetic field is

$$\frac{d^2E}{dt^2} - \cdots - \frac{3}{2}\cdots - \frac{d^2B}{dt^2}\cdot\frac{dB}{dt}\cdots\frac{dE}{dt} - \frac{1}{B}\frac{dB}{dt}E = 0$$

Using Floquet's theory and a perturbation treatment, Burger[2] et al. derived the energy increase rate when a sinusoidal perturbation is applied. The energy increase rate (or heating rate) is

$$\frac{dE}{dt} = \frac{\delta^2}{6}\,\frac{\nu_c\,\omega^2}{\frac{9}{4}\nu_c^2 - \omega^2}\,E,$$

In later work,[3] it was found that a sawtooth perturbation satisfies the condition for first order (in δ) heating, and the heating rate for this case (sawtooth) is

$$\frac{dE}{dt} = \frac{\delta\omega}{3\pi}E$$

This can be an improvement of two or three orders of magnitude on the sinusoidal case. Small values of δ are also easier to achieve experimentally.

Experimental data, including such plasma characteristics as P, T_e, T, n_e and type of gas will be discussed, and heating of ions and electrons as functions of magnetic induction, electron number density, and neutral gas pressure will be presented. The detailed design of the above apparatus will also be presented and discussed.

1. Min Wu, L. Jiang and J. R. Roth, "Experimental Results on Collisional Magnetic Pumping in a Modified Penning Discharge with Magnetic Mirror Configuration", APS Bulletin Vol. 33, No. 9, p2019 (1988).

2. J. M. Berger, et al., "Heating of a Confined Plasma by Oscillating Electromagnetic Fields", Phys Fluids, Vol. 1, No. 4, pp 301-307, (1958).

3. M. Laroussi and J. R. Roth, "Analytical, Computational, and Experimental Results on Plasma Heating by Collisional Magnetic Pumping", APS Bulletin 32, No. 9, p. 1950, (1987).

*Supported by AFOSR contract 86-0100 (Roth)

Wu, M. and Roth, J. R.: "Plasma Heating by Collisional Magnetic Pumping in a Steady-State Modified Penning Discharge", Proceedings of the 1989 IEEE International Conference on Plasma Science, May 22-24, 1988, Buffalo, NY (1988).

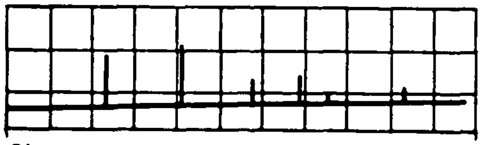
Steady-State, Gas-Filled Orbitron Maser

Mark Rader, Fred Dyer, and Igor Alexeff*

The University of Tennessee

The Gas-Filled Orbitron Maser[1,2] operates reliably in the steady-state. The output consists of narrow lines that do not shift in frequency as the discharge current is varied. A typical spectrum of the microwave emission is shown below.

TYPICAL HIGH FREQUENCY ORBITRON SPECTRUM



The primary reason that the device was previously operated in the pulsed mode was because the device was intended as a very-high-frequency source. Since the frequency scales as the square root of the applied voltage, and a gas-filled device cannot hold off voltages much over 1000 V, pulsed operation was used to obtain high transient voltages. However, steady-state operation is much more convenient for studying the physics of the device. The line spectrum emitted suggests that the alternate explanations of Orbitron operation as two interpenetrating electron beams involved in a beam-plasma interaction is not applicable here[3,4,5]. Our belief that particle orbits produce the radiation, and not three wave mixing, is also supported by the fact that we have observed a large potential drop between the anode and plasma thus indicating the presence of a large potential well.

*Work supported by the Airforce Office of Scientific Research. Contract #AFOSR-86-0100.

1. I. Alexeff and F. Dyer, 1980, Physical Review Letters, 45, 351.
2. V. Granatstein and I. Alexeff, High Power Microwave Sources, Artech House, p. 293, 1987.
3. R. W. Schumacher and R. J. Harvey, in 1984 IEEE Int. Conf. Plasma Science, Conf. Rec., p. 109.
4. R. W. Schumacher and R. J. Harvey, Bull. Amer. Phys. Soc., vol. 29, p. 1179, Oct. 1984.
5. R. W. Schumacher, Bull. Amer. Phys. Soc., Vol. 29, p. 1601, Nov. 1986.

Rader, M.; Dyer, F. and Alexeff, I.: "Steady-State, Gas-Filled Orbitron Maser", Proceedings of the 1989 IEEE International Conference on Plasma Science, May 22-24, 1989, Buffalo, NY (1989).

A Visible Plasma

I. Alexeff, Fred Dyer and Mark Rader*

University of Tennessee

We have obtained a steady-state plasma with the plasma frequency in the visible. Thus, in principle, phenomena such as the production of electron plasma oscillations can be observed visually. The plasma frequency is given by,

$$\omega_{pe} = \left(\frac{ne^2}{\varepsilon_0 m_e} \right)^{1/2},$$

here ω_{pe} is the plasma frequency (radians/second), e is the electron charge (1.6×10^{-19} coulomb), ε_0 is the permittivity of vacuum (8.85×10^{-12} farad/meter) and m_e is the electron mass ($.91 \times 10^{-30}$ kg). Our contribution is in noting that metallic cesium both has a very low value of free electron density, n, due to its bloated atomic size, and a large number of bound electrons (54) that are polarizable and increase the value of ε to 1.4165 ε_0. The low value of electron density alone results in a plasma frequency corresponding to light at 3630 Å (the ultra-violet), but adding in the correction to ε_0 results in a wavelength of 4320 Å, which is in the blue. We have succeeded in photographing the blue light penetrating above the cutoff at ω_{pe}. We note that R. W. Wood[1] states in his book, Physical Optics, that "The case of caesium is especially interesting as its region of high transparency begins in the visible violet, and films of the proper thickness transmit light of a rich violet color as deep and pure as that transmitted by a strong solution of cuprammonium or dense cobalt glass". Wood finds an experimental cutoff frequency of 4400 Å, but does not correlate this number with plasma effects. Further applications will be discussed.

*Work supported by Air Force Office of Scientific Research. Contract #AFOSR-86-0100.

1. Robert W. Wood, "Physical Optics", (Dover, New York, 1967), page 560.

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APPENDIX H

Title Pages and Abstracts of Graduate Theses Completed with The Support of Contract AFOSR 86-0100

PLASMA HEATING BY
COLLISIONAL MAGNETIC PUMPING

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Mounir Laroussi

June 1988

ACKNOWLEDGEMENTS

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Special thanks go to his wife Nicole C. Laroussi for her support and her constant help in typing the early drafts.

Finally, the author wishes to express his unbounded appreciation to his parents for their relentless support and encouragement throughout his academic career.

This work was supported by the Air Force Office of Scientific Research under contract 86-0100 (Roth).

ABSTRACT

Collisional magnetic pumping as a plasma heating method is investigated theoretically, computationally, and experimentally. Improvement of the efficiency of this heating method is also achieved. The theoretical treatment yields solutions to the energy transfer equations. The solution is presented in the form of an energy increase rate, which gives quantitatively the amount of energy increase per RF driving cycle. The RF wave adds a small perturbation to the background steady state DC magnetic field that confines the plasma. Depending on the type of waveform used, the energy increase rate obtained can be of first or second order in the amplitude of the magnetic field perturbation.

Two waveforms are used in this work. The first is a sinewave with variable frequency and amplitude. The energy increase rate in this case is proportional to the second power of the magnitude of the perturbation. This yields a small amount of heating for small perturbations. The second waveform used is a sawtooth with adjustable frequency and amplitude. The energy increase rate in this case is proportional to the first power of the magnitude of the perturbation. This yields an improvement of several orders of magnitude over the previous case.

Two circuits have been implemented to study experimentally the effects of the above mentioned perturbations on a cylindrical plasma generated by a classical Penning discharge. The circuit generating the sinusoidal perturbation is a high-Q parallel resonant circuit with tunable resonance frequency. The circuit generating the sawtooth perturbation is a switch-mode configuration using state-of-the-art metal-oxide-semiconductor transistors

capable of switching on and off in few tens of nanoseconds and of handling high curents and voltages. The experimental heating data collected in both cases is presented and discussed.

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CONVERSION OF THE HP3577A NETWORK ANALYZER TO A SPECTRUM ANALYZER MODE OF OPERATION WITH LOW NOISE AND CROSS-TALK

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

John E. Crowley

March 1987

APPENDIX J

Trip Reports Prepared Under Contract AFOSR 86-0100

TRIP REPORT TO THE 18th INTERNATIONAL CONFERENCE ON PHENOMENA IN IONIZED GASES

Swansea, Wales
July 13-17, 1987

by

J. Reece Roth
ONR contract N00014-80-C-0063
AFOSR contract 86-0100

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FORWARD

This report describes the 18th International Conference on Phenomena in Ionized Gases, which was held in Swansea, Wales, July 13-17, 1987. Two representatives of the UTK Plasma Science Laboratory attended. Prof. J. Reece Roth was supported by AFOSR contract 86-0100 (Roth), and Mr. Paul D. Spence by ONR Contract N00014-80-C-0063.

TRIP REPORT ON THE 18TH INTERNATIONAL CONFERENCE ON PHENOMENA IN IONIZED GASES

The Conference and Its Antecedents

The International Conference on Phenomena in Ionized Gases, which was held from the 13th to to the 17th of July 1987, in Swansea, Wales, was the 18th in a series which began at Oxford in 1953. This conference has been held in various European countries every two years since that time. The scope of this conference excludes fusion related plasmas, high temperature plasmas, astrophysical plasmas, waves and instabilities in plasmas, and atomic collisional or ionization phenomena. The conference includes gaseous discharges and low temperature plasma physics, both theoretical and applied. English is the official language of the conference. The conference is managed by a 12-person international scientific committee, the members of which are each from different countries.

The scientific program of the conference features 45 minute general invited lectures which review a broad field of interest, of which there were eleven in the mornings of each day. The conference also featured 26 topical invited lectures of 30 minutes each which are presented in two parallel sessions in the afternoons of the conference. Finally, contributed papers were presented, all in poster format, during the afternoons of the conference. As in previous conferences the papers were submitted approximately 6 months before the conference date, reviewed, and published in the form of a four volume proceedings which was distributed to the participants as they

registered at the meeting. The invited papers will be published after the meeting and sent to the conference participants approximately 6 months after the conference.

Some statistics of the conference may be of interest, which illustrate its international character. There were 434 contributed poster papers at this meeting. There were approximately 550 participants at the conference, including 55 accompanying persons (spouses, etc.) from 33 countries. Among the national delegations, there were 93 individuals from the United Kingdom, of which 41 were not from the University of Wales in Swansea. The next largest delegation was from West Germany with 49 people. There were 46 participants from the USSR, 39 from France, 38 from Japan and 34 from the United States. Among a random selection of other countries, there were 17 participants from the Netherlands, 12 from Yugoslavia, 12 participants from Hungary, 11 from Poland, 9 from Australia, 8 from Italy, 5 from Canada, and 4 from mainland China. In most cases, these numbers are a fair reflection of the amount of low temperature plasma research and development in the respective countries. An exception is the United Kingdom, where approximately 50 of the 93 UK participants were from the University of Swansea, and many of these were not plasma physicists, but were graduate students or staff members who were helping with the organization and running of the conference. With 34 participants, the U.S.A. was definitely under-represented with respect to the amount of relevant plasma research going on in this country; this under-representation carried over into the invited and contributed papers as well, with few US researchers giving

features of the JET facility were explained to us. That Saturday happened to be a good time for such a tour, since the facility was not operating, and was opened up so that it could be inspected by members of the public, behind its shielding wall. There is no doubt that this facility is extremely well engineering and very impressive in its size and overall design. It is now fitted with both neutral beam injection and rf heating, and their experimental program is now experimenting with magnetic neutral points and magnetic divertors as a means of purifying the plasma (the JET plasma is extremely dirty by large fusion machine standards, with Z_{EFF} ranging between 2 and 5 for most of their runs). They have been unable to operate the JET facility in the H-mode when the magnetic neutral points and the magnetic divertors are on field lines whch are closer to the plasma than the material limiters or the walls.

invited papers, and many of the US participants at the conference not having contributed papers on the program.

The conference was held at the University College of Swansea of the University of Wales. The city of Swansea is on the southern coast of Wales, approximately halfway between the English border and the westernmost extremity of the Welsh peninsula. The University is located in a very attractive, park like campus. The logistical and social aspects of the conference were extremely well organized by the staff of the University College of Swansea. The scientific sessions ran morning and afternoon and were not carried over into the evenings, which were kept free for such cultural activities as a string quartet concert, Welsh folk dancing, a banquet at the Swansea Town Hall, and the conference banquet on Thursday evening. Wednesday afternoon was unscheduled and kept free for tours; the conference was completed by noon on Friday, thus allowing the participants an early start on their way home.

I personally found the contributed papers to be generally more interesting and of a higher standard than the invited papers. The general and invited lectures were often of very disappointing quality. Rather than the broad, integrative survey lecture that the audience had a right to expect, the invited speakers too often said at the beginning of their lecture that the topic which they had been invited to cover and which they had accepted an invitation to cover was too broad, and that they would specialize to a narrower scope, which included their own work and that of a very few others. Many of the invited lectures also were disappointing in being poorly researched, poorly organized, or having inadequate visual aids. Some clearly were prepared at

the last minute in the form of handwritten visual aids on transparencies provided by the conference secretariat. This tendency to waste the time of the audience on inadequate invited speakers has been a characteristic shortcoming of this conference for the entire time that I have been familiar with it (I first attended this series of conference in 1967). Part of the problem with the invited speakers probably is a reflection of the way in which the conference is run, by a 12 person international scientific committee containing only one representative from the US, West Germany, and Japan, three countries that are probably doing more than half the work in the field covered by the conference. In the closing ceremony, it was announced that Dr. Authur Guenther of the Air Force Weapons Lab, Kirtland Air Force Base, had been elected as the US representative to the International Scientific Committee.

Technical Overview of Conference

The last times that I attended this series of conferences was in 1967 in Vienna, Austria, and in 1969 in Bucharest, Romania. In the intervening years, when I have had support to attend international conferences, I have attended the conferences on Waves and Instabilities in Plasmas, since that conference was more relevant to my research interests. However, the failure of the Kiev International Conference on Plasma Physics this year left this conference as the most appropriate second choice. Being away from the conference for a period of 18 years allowed me to view this conference with a perspective different from those who have attended it regularly, and to better identify some significant changes which have occurred over that time. 20 years or so ago, the work reported at this conference was more basic, more academic, and more theoretical than the papers which were presented in Swansea this year. It was evident that there has been a sea change in the emphasis of research in this general area in all of the industrialized countries that were represented. The focus on low temperature plasmas and gaseous discharges has remained substantially the same. The change has been from theoretical, academic, and basic research to specific industrial and commercial applications, or to phenomena that have some identifiable application to commercial or military applications.

This shift in the emphasis of the conference from theoretical to applied manifest itself in several ways. For example, I have the definite impression that there were many more representatives at this conference from industrial laboratories (outside the US) than attended it 20 years ago. In addition, many topical areas which were of academic or theoretical interest and which were

well represented 20 years ago scarcely appeared on the program of this conference at all. An example of this is the interest in moving striations, propagating waves which are observed in the normal glow discharge at pressures on the order of 1 to 10 torr. These propagating waves represent one of the oldest problems in plasma physics, having been observed by Michael Faraday in the 1830's. In spite of much research over more than a century, there still does not exist a satisfactory theory to describe their behavior or dispersion relation. There were perhaps 20 or more papers on this subject in the conferences of 20 years ago, but at this conference there were no more than three or four. In fact, a center of moving striation research at the Institute of Plasma Physics in Prague, Czechoslovakia, did not have a representative at this conference. I would estimate that well over half of the papers were motivated by applications to lasers, to plasma processing of materials, or military applications involving the interaction of laser radiation with matter.

Survey of Selected Invited Papers

In this section, I will summarize those invited papers at the conference which I was able to attend. This included all of the general invited lectures given in the mornings, and nearly half of the topical invited lectures. The latter were scheduled in parallel, in the afternoon, in such a way that it was not possible to attend more than half of them. Full length versions of these invited papers are to be published 6-9 months after the conference.

On Monday morning, A. V. Phelps of the Joint Institute for Laboratory Astrophysics (JILA) in Boulder, presented a paper on discharges at extremely high values of E/N and low currents. The parameter E/N is more usually expressed as the ratio of the electric field in volts per centimeter to the

background neutral gas pressure in torr, p, and is a very important similarity parameter in low temperature gaseous discharges. Normally the electric field E is independent of discharge current up to about 10^{-4} amperes, and over the pressure range from 0.1 to 1 torr. In conventional low temperature gaseous discharges, the value of E/p might range up to perhaps 100 volts per centimeter-torr. By high values of E/p, Phelps had in mind values of several thousand to 10^4 volts per centimeter-torr. He discussed some of the physical phenomena that were characteristic of these high values of E/p, which in argon included excitation of forbidden lines by fast neutrals in the gas, and ionization by fast ions at values of E/p above several times 10^4 volts per centimeter-torr.

The second general invited lecture on Monday was given by Botticher from East Germany, who spoke on ionization kinetics in shock heated rare gases. The experimental work on which he reported was done in shock tubes with very high pressure ratios between the drivng and driven gas. His research looked very much like a resurgence of the shock tube work that was supported by the Department of Defense in the late 1950's and early 1960's, with one exception, and that was his accounting for non-maxwellian electron energy distributions.

On Monday afternoon F. Leuterer of the Max Planck Institute for Plasma Physics in Garching, West Germany gave a talk on current drive in the ASDEX tokamak with lower hybrid waves. I have summarized this talk in a later section of this trip report on the fusion related activities at this conference.

Also on Monday afternoon, K. Szego from Budapest, Hungary gave a talk on plasma phenomena around a comentary nucleus. This paper summarized European results from space probes that passed near Halley's comet. It was particularly interesting, inasmuch as the United States had no probe of its own for the measurements that were reported by Szego. This was virtually the first time that any kind of quantitative scientific measurements had been made by a space probe in the near vicinity of a comet. Much of the data were the first of their kind, and many unanticipated phenomena were observed. Traces of ice and bursts of heavy ions were observed by the space probe as far as 28 million kilometers away from the comet. As the probe approached to 7 or 8 million kilometers, hydromagnetic waves were observed in the magnetic field embedded in the interplanatery medium. The waves had very large ratios of the magnetic field fluctuation amplitude to the mean background value, which ranged from 20 to 50%. It was concluded that much energy was carried away from the bow shock of the comet by ion Alfven waves. Szego also remarked that particles seemed to be accelerated by stochastic mechanisms, including scattering on turbulent lenses of plasma, and they found that the particles became more isotropic as they approached the bow shock of the comet. This turbulent heating would seem to be similar to that which we are studying in the UTK Plasma Science Laboratory, and have observed in the modified Penning discharge experiment as part of our ONR contract.

Also on Monday afternoon, Hans Pecseli of the Riso National Laboratory in Denmark gave an invited talk on conditional eddies or clumps in ion beam driven turbulence. This paper was of great interest to Paul Spence and I, since

he has taken measurements on a Q- machine which are similar in kind to the active plasma turbulence measurements that Paul Spence and I have made on the modified Penning discharge recently for our ONR contract. Pecseli did selective sampling of data from two potential fluctuation time series taken from his Q- machine plasma. The selective data sampling consisted of digitally sampling signals with amplitudes above a threshold, in a way that simulates the kind of selective sampling that is done with an oscilloscope when one adjusts the trigger signal for the oscilloscope in such a way that only signals with a high initial amplitude are displayed. He reasoned that signals with relatively high amplitudes above a threshold would in some sense be more characteristic than the random or stochastic signals of lower amplitude. He found that, in his Q- machine, axial electrostatic potential wells form and propagate along the beam direction. This velocity was measured and was found to be less than the velocity of the beam ions in this experiment.

The amplitudes which he looked at were in the highest ten percentile of the fluctuating electrostatic potential signal in his plasma. He made the point that these axially propagating coherent structures were not too rare. As a whole, the physics of his Q-machine was somewhat different from our experiment at UTK, which does not have an axial ion beam in it. However, his time series analysis from two separate digitally sampled probes was very similar in general philosophy to ours. In addition, he discussed in a contributed paper the observation of azimuthally propagating rotating spokes, which were apparently driven by E/B drifts, and which resemble the strong radial spokes which are frequently observed in our modified Penning discharge at UTK.

Finally, Y. Nakamura from Japan presented a topical invited lecture on experiments on ion acoustic solitons in a multicomponent plasma with negative ions. The work which Nakamura presented was apparently motivated by practical applications to electrical switchgear, where negative ions play a role. His experimental arrangement put a high negative pulse on a grid which was located in the middle of a sulfur hexaflouride plasma at a pressure of 1 to 2 x 10^{-4} torr of argon, with the sulfur hexaflouride (the species which produced the negative ions) having a partial pressure that ranged up to 2 x 10^{-4} torr. He found that the negative sulfur hexaflouride ions gave negative solitons with a negative pulse on the grid in his plasma.

The first general invited lecture on Tuesday morning of the conference was by W. Witteman from the Netherlands, who gave a very interesting talk on excimer lasers. He characterized excimer lasers as operating between 120 and 640 nanometers, and containing such diatomic rare gases are Ar_2 and Xe_2, as well as chemical combinations of the rare gases with flourides or halides. The molecules used in excimer lasers are stable in an excited state but dissociate when a photon is emitted. The interest to this conference was that gaseous discharge plasmas are used to create excimer lasers, and the efficiency of pumping the lasers is a key issue that involves much gaseous discharge physics. In the kind of excimer laser he discussed, pre-ionization technology is important. They typically use high voltages and high currents produced by a one megavolt Marx generator. Their E-beam laser pump had a current rise time of 50 nanoseconds and produced a relativistic electron beam with a current density of 300 amperes per square centimeter. This device had a discharge efficiency less than 10% and typcially was in the range of 2 to

4.2%. Witteman stated that the experiment and theory were in good agreement in predicting the efficiency of the discharge. Some of the problems which they had in their experiment were in getting a homogeneous glow discharge which could be pumped by the relativistic electron beam. The background electron number density was about 10^7 electrons per cubic centimeter prior to the electron beam pulse, and was about 10^{14} electrons per cubic centimeter during the electron beam discharge. He remarked that microwave excitation of these excimer lasers did not appear to be useful because the electron energies are too low to excite the short wavelength lines of interest.

The second general invited lecture on Tuesday was given by A. H. Guenther of the Kirtland Air Force Base. Art Guenther gave a very well organized and well presented lecture on optical control of gaseous discharges, in which he surveyed the many fast switching techniques which have been developed by his AFOSR program at Kirtland, with emphasis on those that use optical control to initiate breakdown. He showed slides and data from the unclassified fast triggering system which has been developed for the PBFA-2 inertial fusion experiment at the Sandia Laboratories. He pointed that in this experiment, all 36 switches fired within two nanoseconds.

The third and final general invited lecture of Tuesday morning was by W. Ebeling of East Germany, who spoke on instabilities and phase transitions in dense hydrogen, rare gases and alkali plasmas. This was an interesting and highly mathematical presentation in which some of the classical methods of solid state physics and nonequilibrium thermodynamics were applied to dense plasmas. Ebeling felt that the methods which had been applied to

semiconductors could provide useful estimates of the effective diffusion coefficients in dense plasmas under conditions of high density, and large free energy densities. For specific mathematical results of Ebelings work, we will have to wait approximately 6 months until full length versions of the invited talks are published.

On Tuesday afternoon, Allen Rees of the University of Liverpool gave a topical invited lecture on plasma and plasma assisted processing of semiconductor materials. The work which he described was largely his own and was motivated by the application to integrated circuits. He pointed out that semiconductors must be etched to a scale of 1 micron or less, and that to assure reliability, the etching must not be damaged around the gate of the semiconductors, which is often smaller than 1 micron. He characterized typical plasmas used for plasma etching and which are generated by microwave power as having electron number densities of 5×10^{10} electrons per cubic centimeter. He also mentioned briefly the application of plasma processing to integrated optical electronic devices intended for fiber optic applications.

Although one of the disappointments of the conference was the absence from the program of any paper on recent developments in diamond deposition, there was an excellent general invited lecture on Wednesday morning by J. Perrin of the Ecole Polytechnic in France on the multidisciplinary task of plasma deposition studies; the growth of hydrogenated amorphous silicon induced by silane discharges. This invited paper described a process very closely related to the more interesting diamond deposition, the plasma assisted chemical vapor deposition processes which results in the growth of

very pure silicon by silane discharges. Silane is a compound of silicon and hydrogen, the chemical formula of which is SiH_4. When an rf discharge is made in this gas, under pressures which range from 10^{-4} to 1 torr and electron number densities from 10^4 to 10^{11} per cubic centimeter, very pure silicon can be deposited on surfaces in contact with the silane plasma. The deposition rates discussed by Perrin ranged from .01 to 10 angstroms per second. The percentage of ionization in these discharges is less than 0.1%, and the electron kinetic temperatures are quite low, ranging from 0.1 to 5 eV. The energy fluxes resulting from this deposition range from 0.01 to 1.0 watts per square centimeter. The overall impression given by Perrin's talk was of a relatively mature technology, with techniques well in hand for building up layers of very pure silicon and other materials.

The second general invited lecture, the last scheduled for Wednesday, was by A. S. Trubnikov and M. V. Nezlin from the Kurchatov Institute in Moscow, who presented a general invited lecture on analog simulation study of drift vortices (solitons) in plasmas and spiral structures. Trubnikov attended the conference and presented the paper. He made the point that solitons can determine transport processes in plasmas, including plasmas of thermonuclear interest, and are therefore well worth studying. With that brief initial remark, he cast loose completely from plasma applications with the comment that one could draw an analogy between water waves and plasma gradient drift waves. The analogy to the plasma drift waves that he discussed was a parabolic sheet of water maintained on the inner surface of a rotating axisymmetric parabolic cup. Surface waves on this parabolic sheet of water which were produced or modified by an external perturbation, were an

analogy to what can happen with gradient plasma drift waves of interest in fusion plasmas. Much of this talk was devoted to discussion of a movie of an actual experiment which was done with probably a few dollars worth of equipment, including a rotating parabolic cup on a turntable, with the parabolic surface of the water illuminated in such a way that surface waves and their perturbations could easily be seen. When the perturbation took the form of a latitude-like annular disk on the surface of the parabola, the resulting vortices looked cyclonic in character. Semi-permanent, soliton- like structures very reminescent of cyclones on the surface of the earth or the great red spot on Jupiter maintain themselves for relatively long periods of time. Under certain conditions, one could see stable, spiral-arm like structures which resemble the rotating spokes which develop in magnetrons, or in galactic spiral arms. The movie was a very interesting illustration of nonlinear fluid dynamics, but the connection to phenomena in plasmas was not clear, but may be made so in the published version of these invited talks.

The first general invited lecture of Thursday was presented by F. Weinberg of Imperial College, London, who spoke on combustion and plasmas. He mentioned that typical flames may have an electron number density of 10^{10} electrons per cubic centimeter, with typical ionic species in flames being OH^-, and HCO^+. In zero gravity, flames apparently are spherical, and one can direct flames in zero gravity by electric fields. He described flames as plasmas, ignition of flames by plasmas, and the use of plasma jets in combustors. In the latter two areas, he pointed out that such things as plasma jet spark plugs were developed for aircraft, and were found to be reliable. He pointed out that electrically augmented flames, that is plasma jets and

plasma torches, had a history that went back at least to 1924. According to Weinberg, interest in electrically augmented flames peaked in the 1960's and 1970's with the prospect of cheap nuclear electricity, but interest has receded in recent years when it appeared that this was not going to happen. He showed some very interesting and very elegant diagnostic data which were obtained by laser induced florescence of OH^- present in the flame that he was studying.

The second general invited lecture on Thursday was by M. I. Rabinovich from the Institute of Applied Physics in Gorky, Russia, who spoke on dynamical chaos in plasmas. This lecture was highly mathematical, and full appreciation of Rabinovich's point will have to wait for publication of his paper in the invited conference proceedings. He did claim to have demonstrated the random behavior of a strictly deterministic system which is relevant to plasmas. He showed us several phase plots which showed chaotic motions resulting from the dynamics of Langmuir solitons in plasmas. His mathematical approach appeared to be based on systems of first order, nonlienar Volterra equations, very reminescent of the approach published about 15 years ago by Manheimer and Flynn of the Naval Research Laboratory, although Rabinovich's work has gone considerably further than theirs.

The first topical invited lecture which I attended on Thursday afternoon was by Yu. I. Ostrovskii, of the Ioffe Institute in Leningrad, who spoke on holographic interferometric diagnostics of plasmas. Perhaps the most interesting single feature of his talk was his willingness to commit himself to a quantitative measure of the sensitivity limit of this method of differential

density measurement, which was expressed in terms of the index of refraction of the plasma, the probing wavelength, the electron density, and the plasma thickness. He mentioned that high quality recording materials (by which he meant photographic plates) was a problem. The measurements which he showed us were taken on the tokamak AT-2.

Another interesting topical invited lecture on Thursday was by G. N. W. Kroesen of the Eindhoven University of Technology in the Netherlands, who spoke on possibilities and limitations of plasma deposition. This paper was concerned with a chronic problem in the field of plasma deposition and etching as applied to integrated circuits: measurement of the surface deposition rate as the etching or deposition process is occuring. He had some data on the transport process from the plasma glow discharge through the sheath to the surface. In his laboratory the deposition rate is measured by an unusually sophisticated form of in situ ellipsometry, which is an optical arrangement for studying the thickness thin films on solid surfaces. It relies on the fact that if plane polarized light is incident on a thin surface, it is reflected as elliptically polarized light. Th^ degree of ellipticity in the reflected beam depends the thickness of the film, and thereby allows measurement of the film thickness as it is deposited by the plasma.

A change of pace in the topical invited lectures was provided by T. E. Allibone of the City University of London, who is in his late 70's or early 80's, and is still doing publishable research in the field of high voltage dc breakdown. According to Allibone, there has been a recent resurgence of interest in dc high voltage breakdown because of the use of extra high voltages by the electric utilities for long distance or under water power

transmission. He devoted his talk to some observations on the basic physics of dc breakdown in atmospheric air, an area in which apparently there is still much to be learned. He was able to make some new observations because the high voltage laboratory at the City University of London has no windows and it is possible there to watch the high voltage breakdown process in its entirity under very low levels of interfering background light. When two meter diameter spheres, charged to voltages between 1/2 and 1 megavolt dc, were observed in the dark with their surfaces sidelighted, the side illumination made evident dust particles which were drawn to the surface of the sphere where the electric field was highest. These dust particles stacked up into whisker-like structures, which finally became of such length that they broke loose from the surface and then traveled along electric field lines to the opposite electrode, where they received the opposite electrical charge, and continued to build up their length. These whiskers would slosh between the two electrodes in turn. Because the electrodes were spherical, and the electric field lines curved, they would walk away from the center line. These whiskers seemed to play a role in streamer formation and in the breakdown process. According to Allibone, the formation and disappearance of these streamers off to one side of the electrodes would continue until the dust of which they were formed was cleared away from the surface of the sphere. He attributed the well known fact that large spheres at megavolt potentials in air have to go through a conditioning process before they will hold off high voltages, to the formation and cleaning up of these whisker-like structures in the gap between the two spheres.

The conference finished at noon on Friday, during the morning of which there were only two general invited lectures. The first of these was by H. R. Greim of the University of Maryland, who spoke on Stark broadening and shifts of spectral lines in plasmas. This was an excellent tutorial and survey lecture on the subject, which I look forward to seeing in the printed conference proceedings. It started by reviewing material on Stark broadening which can be found in Greim's book on Plasma Spectroscopy, which is now at least 20 years old, and brought it up to date with recent data and techniques, particularly the active laser based plasma diagnostic methods.

The final general invited lecture of the conference was given by W. Englehardt of the JET Joint Undertaking at Culham, who gave a lecture on heating and confinement of plasmas in the JET tokamak. A discussion of this invited talk may be found in the section of the trip report on fusion related issues.

Survey of Selected Contributed Papers

There were too many contributed papers at this conference to comment on individually, or even grouped into the 18 subject areas used to organize the conference.

Three papers by H. L. Pecseli from Risco on pages 360, 362, and 368 of the Proceedings were of particular interest to us here at UTK. These papers reported more detail than Pecseli gave in his invited talk, on his experiments using digital time series analysis techniques to analyze the nature of fluctuations and turbulence in his plasma. In this Q-machine plasma, he was able to demonstrate the formaiton and long lifetime of E/B driven rotating spokes on the edge of the plasma. These spokes were formed by active

perturbation of a probe at the edge of the plasma, and consisted of vortex-like structures with an axial extent that covered almost the full length of the plasma. The quantity measured in Pecseli's experiment was the fluctuating electrostatic potential, measured with floating Langmuir probes. Some runs also were made in which density fluctuations were measured, under the assumption that the density fluctuations were proportional to fluctuations of the ion saturation current of a Langmuir probe. The Q-machine plasma studied by Pecseli was far less turbulent than our modified Penning discharge, and had no strong radial or axial electric fields imposed on it.

On Tuesday afternoon there was a large poster session of contributed papers on waves and instabilities, including self-organizing processes, which reflected the current interest in plasma turbulence and nonlinear processes. There were many Russian papers in this area. A second session of contributed papers on Tuesday covered the area of generation and dynamics of plasma flows, none of which seemed to be motivated by aerospace applications, but most of them having some obvious relation to commercial materials processing.

On Wednesday morning there were two sessions on plasma chemistry and plasma surface interactions which did not seem to contain anything very new, and all of which seemed to be motivated by industrial applications to integrated circuit fabrication.

On Thursday afternoon there was a surprisingly small session on numerical modeling, leading me to think that not nearly enough of the right kind of work on plasma simulation is being done in the low temperature, relatively high density regime of industrial interest. Also on Thursday

afternoon were many papers on rf and dc glow discharges of a kind used in plasma etching and deposition, again motivated by applications to integrated circuit fabrication.

Mr. Paul D. Spence, GRA on our ONR contract, also attended this conference, and contributed the following: "Two poster papers were of particular relevance to our work on Penning discharge plasmas. The first of these was a theoretical paper by Duk-In Cho and Bong Guen Hong of the Kaist Physics Department in Seoul Korea and W. Horton of the University of Texas, Austin. This paper was titled "Nonlinear Study of Collisional Drift waves in a Partially Ionized Plasma" and is applicable to low β plasmas. Using two fluid theory and including temperature gradient effects, finite heat conductivity, and perpendicular ion viscosity, the authors were able to derive a dispersion relation and growth rate for drift waves. The effect of finite thermal conductivity was shown to increase the growth rate. A temperature gradient was shown to be stablizing for long wavelengths, and perpendicular ion viscosity stabilizing for short wavelengths. These results are directly applicable to the drift wave studies on the Penning discharge. The authors were also able to renormalize the two fluid equations using the direct interaction approximation (DIA) of weak coupling theory. An approximate spectral formula was presented from which an anomalous electron diffusion coefficient and thermal conductivity were derived. These results indicated that the main contribution to transport is due to the low k part of the turbulent spectrum. This result complements our interest in the modification of edge turbulence using active techniques. The second paper was an experimental paper by S. Iizuka, H. L. Pecsel, and J. Jul Rasmussen of the

Riso National Lab, Denmark, entitled "Experimental Investigation of Flute Type Turbulence." The authors investigated spontaneously excited turbulent electrostatic fluctuations due to flute type structures in a low beta Q-machine. The central column of the plasma discharge studied was surrounded by a residual plasma characterized by a large radially increasing D. C. potential. This profile resulted in E x B azimuthal drift. The turbulent electrostatic fluctuations studied were confined radially to a narrow region of this edge plasma where azimuthal velocity shear was maximum. In this region fluctuations were characterized by $e\phi/Te >> n/n_0$ implying that electrons did not maintain an isothermal Boltzmann distribution. This is counter to the common assumption in drift wave studies that electrons do maintain a Boltzmann distribution.

By the injection of an externally excited cell the authors investigated the nonstationary properties of the correlation function for potential fluctuations. The induced uniform convection of the turbulent flow field past detection probes introduced a transient response to the correlation function. A transient increase in the correlation length resulted and hence resulted in a cascade toward longer wavelengths in the energy spectrum. This result may explain some of the inverse cascade observed on our Penning discharge studies under coherent external excitation."

Tour of the JET Fusion Facility

Since 1965, the program committee of this conference has rejected any papers submitted in the field of fusion energy and has excluded high temperature plasma physics and fusion from the scope of the conference.

However, the International Scientific Committee has attempted to keep the conference participants abreast of advances in the field of fusion energy by offering a couple of invited papers on current progress in fusion energy for the information of those attending. On Monday afternoon, F. Leuterer gave a topical invited lecture on "Current Drive n the ASDEX Tokamak with Lower Hybrid Waves." This paper was poorly attended, but reported on one of the major tokamak experiments in Europe, which is a joint effort, located in Germany, by several European countries. International cooperation on the ASDEX experiment extends to the United States, where an international cooperative agreement and an exchange of research personnel are in place, along with partial funding of ASDEX by the U.S. fusion program. This facility is located at the Max Planck Institute for Plasma Physics in Garching, West Germany. It is a D-shaped tokamak, with a major radius of 1.65 meters, a minor radius in the equatorial plane of 40 centimeters, magnetic inductions of up to 2.8 tesla, toroidal currents between 300 to 400 kiloamperes, and it has the capability of up to 2.4 megawatts of rf plasma heating power at 1.3 GHz.

The ASDEX tokamak is noted for being the first to observe the so-called "H-mode" of confinement, in which the plasma confinement time was observed three or four years ago to be about twice that predicted by the phenomenological scaling laws available up to that time. The physical mechanism responsible for this improved confinement in the H-mode has not been identified, but the research program on ASDEX has identified several factors which are associated with this improved containment. These factors include an isolation of the toroidal plasma from the walls and limiter by closed particle drift surfaces, and the maintenance of a very low impurity level in the

plasma. While in the H-mode, experiments have been conducted on rf current drive in the plasma, in which lower hybrid radiation is beamed tangentially in the equatorial plane of the torus, in such a direction as to impart momentum to the electrons that maintain the toroidal current in the plasma. By this means the researchers on ASDEX have maintained the plasma in a quasi steady state, in which all of the ohmic losses of the toroidal current have been made up by momentum transfered by the rf current drive. These researchers have also concluded that in principle it is possible to ramp the toroidal current up from zero without any transformer action whatever in the toroidal plasma, a step which was actually accomplished about two years ago by a Japanese tokamak experiment.

A major issue in the current drive experiments is the efficiency of the current drive, that is, the amps of toroidal current that can be generated per watt of lower hybrid power fed tangentially into the plasma. This current drive efficiency can be expressed as

$$\eta \frac{n_e(m^{-3})I_p(\mathrm{Amp})R(m)}{P_{RF}(\mathrm{watt})}$$

in experiments done in the early 1980's this efficiency factor for a tokamak the size of the ASDEX ranged between 0.1 and 0.2. In the ASDEX experiments, in the H-mode of operation, values of this efficiency factor as high as 0.6 have been observed.

The only other lecture on fusion energy at the conference was delivered by Dr. W. Englehardt, head of one of the experimental group on the JET tokamak at Culham, who delivered a general invited lecture on Friday morning, July 17. His presentation was a curious mixture of encouraging

progress in achieving high plasma parameters in a very large machine, currently the largest in the world, and was discouraging in the very significant areas of physics of which the tokamak community is ignorant. Englehardt mentioned that the JET experiment is now about 1/3 of the way through its overall program, which is currently scheduled to last until about 1991, when the current five-year plan for its operation is scheduled to terminate. It is expected that sometime after 1990, the JET tokamak will burn deuterium and tritium and demonstrate scientific breakeven, that is, more thermal fusion power from fusion reactions, than electrical power needed to maintain the plasma.

The size and plasma parameters of the JET are truly impressive. The toroidal magnetic field is 3.4 tesla over a very large, D-shaped toroidal volume. The toroidal plasma current is five million amperes, with a scheduled increase to seven million amperes being planned. They expect to burn tritium in July of 1991, according to their current schedule of research. Since I heard a similar survey lecture on the JET two years ago, they have added an additional objective to the overall JET program. This is to study alpha particle heating in the plasma when it is burning DD or DT reactions. In this respect, it will duplicate the objectives of the Compact Ignition Torus, an experiment being designed in the United States to replace the TFTR at Princeton and the objective of which is intended to study burning fusion plasmas. The JET tokamak will be much better positioned to study alpha particle heating and burning plasmas, not only because it is a much larger device than the CIT could be, but because the JET facility has a sufficient stored energy capability to be able to operate the plasma for several 10's of

seconds, whereas the CIT will be limited to no more than 5 seconds of flat top operation.

Throughout his talk, Englehardt gave a rather gloomy, though accurate impression of the poor state of theoretical understanding of tokamak physics. He pointed out that the physical phenomena responsible for the Murakami criterion, which determines the MHD stability of tokamak plasmas in terms of a dimensionless parameter based on the magnetic induction, the safety factor, and the major radius, are not known. This parameter is entirely phenomenological, and was first put forward by M. Murakami of the Oak Ridge National Laboratory. The physical basis for this stability criterion is not understood, and Englehardt made no attempt to hide this fact. neither did he make any attempt to hide the fact that the best scaling law for the confinement time in tokamaks, the Kaye-Goldston scaling law, was also phenomenological and that they did not understand the basic physics of the radial transport process by which the particles get from the inside to the outside of the plasma. In this, they are not different from the rest of the tokamak fusion community, but he was unusually forthright about the lack of understanding of basic physics.

There were some other aspects of his talk, however, that suggested that the JET group was unusually weak in fundamentals. One of their problems is the confusion between the particle and energy containment times, and another was their use of the product of kinetic temperature, number density and confinement time as a measure of progress in the field of fusion research. As is well known, and is discussed in Chapter 8 of my textbook, the ion number density, containment time, and kinetic temperature required for a net

power producing fusion reaction can be expressed in the form of a Lawson criterion, a set of curves which is best plotted on a two dimensional representation in which the Lawson parameter, the product of density and containment time, is graphed as a function of the kinetic temperature of a particular fusion reaction, and for a particular powerplant efficiency and other engineering characteristics. About 10 years ago, under pressure of a suggestion by Rand McNally, formerly of Oak Ridge, some members of the fusion community started using the product of number density, containment time and kinetic temperture in discussing the relative status of various fusion experiments, or in comparing the current parameters of a particular machine with the product of these three parameters needed to achieve net power producing fusion reactions according to the Lawson criterion. This product of three parameters is more a public relations than a physics or engineering parameter, since it does not result from any basic consideration of powerplant energy flows or the basic physics of fusion reactions. In spite of this defect, the talk by Englehardt used the product of these three plasma parameters in a very naive way, which suggested that they were unaware of some of the basic power balance considerations which must apply to fusion powerplants.

The third major event relating to fusion energy associated with the conference was a trip to the JET facility at Culham, which happened to be very nearly on a direct line between Swansea and the London airports. This trip was scheduled for Saturday, the day after the conference. Two bus loads, each containing about 50 people, had signed up for the tour of the JET facility. After a ride of approximately three hours, the conference participants arrived at the JET facility and were taken on a walking tour during which the major

Trip Report

PLASMA SCIENCE IN JAPAN

A Trip Report on The 8th International Symposium on Plasma Chemistry and Subsequent Visits to Japanese Plasma Science Laboratories

August 29 - September 12, 1987

by

Prof. J. Reece Roth
University of Tennessee, Knoxville

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by

Prof. J. Reece Roth
Department of Electrical & Computer Engineering
University of Tennessee
Knoxville, Tennessee 37996-2100
(615) 974-4446

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FORWARD

This trip report covers a two week visit to Japan by Prof. J. Reece Roth which lasted from Saturday, August 29, to Saturday, September 12, 1987. The first week of this period was spent attending the 8th International Symposium on Plasma Chemistry, in Tokyo, Japan which was sponsored by the International Union of Pure and Applied Chemistry. The second week of this two week period was spent visiting major plasma science laboratories in Japan, including the Institute of Space and Astronautical Science in Tokyo; the Institute of Plasma Physics in Nagoya, Japan; the Plasma Physics Laboratory at Kyoto University; and the JT-60 tokamak facility in Naka, Japan. Financial support for this trip was provided by the University of Tennessee, with equal support coming from the Center for Materials Processing, Dr. Joseph Danko, Director; the School of Engineering, Dr. William T. Synder, Dean; and the Department of Electrical and Computer Engineering, Dr. Walter L. Green, Head.

A principal purpose of the trip was to present a paper on "Plasma Heating by Collisional Magnetic Pumping for Possible Low Pressure Industrial Application" by myself and Mr. Mounir Laroussi of the UTK Plasma Science Laboratory. A second objective of the trip was to gather fresh material for our junior level course in plasma engineering within the ECE department; and a third objective was to assess the state of development of the field to see whether involvement of the UTK Plasma Science Laboratory in the field of industrial plasma processing was likely to be useful or productive.

THE CONFERENCE ARRANGEMENTS

The 8th International Symposium on Plasma Chemistry was the 8th in a series which has been held in odd-numbered years under the sponsorship of the International Union of Pure and Applied Chemistry. This conference has moved around the world to various cities, and this is the first time, to my knowledge, that it was held in the Far East. I did not attend any of the previous conferences in this series and so am not in a position to compare this conference with its predecessors. In the United States, those who work with industrial applications of plasma processing and thermal plasmas present their work either at this conference, or, in even numbered years, at the Gordon Conference on Plasma Chemistry which is held in alternation with this conference.

The organizers of this conference maintain high standards. Not only an abstract, but a six page, full length paper is required to be submitted by all authors in advance for the Proceedings of the conference. The Proceedings were published in four volumes totalling over 2500 pages, and were given to registrants at the conference. There was a hierarchy imposed on the papers; some papers were presented as posters only, some, such as my own, were presented as 15 minute oral presentations, and a few were presented as half hour invited papers. The schedule of this conference had the peculiar feature that all poster papers were presented on Monday evening, and at no other time during the conference; the remaining four days of the conference were devoted only to oral sessions.

Perhaps because of sponsorship by the International Union of Pure and Applied Chemistry, most of those participating seemed to have backgrounds in chemistry, chemical engineering, or materials science. There seemed to be very few people with plasma physics backgrounds, or who had a sophisticated knowledge of plasma physics or its literature. Attendance at this conference apparently has grown significantly in recent years. I was not able to obtain statistics of previous conferences, but this conference had 677 registrants, of which about 400 were from Japan, and the remaining 270 from other foreign countries. Of these approximately 270 foreign participants, only 37 were from the United States. I am reasonably certain that this dominance of the Japanese researchers is not just due to Japan's geographical isolation; the breadth of participation of Japanese industry in plasma related research, and the large number of Japanese researchers involved in plasma processing appeared to be the dominant factors in the large number of Japanese presenting papers at this meeting. I suspect that there would have been more Japanese papers at this meeting than those of any other country regardless of where in the world this conference had been held. I think it is also worth noting that at the Gordon Research Conference on Plasma Chemistry, which I attended in the summer of 1986, there were approximately 150 people in attendance, including several dozen researchers from outside the United States. I am reasonably sure that most of the people in the United States interested in plasma processing and plasma chemistry were at that conference; I don't think it would be possible to gather together in one place 400 US workers in the field of plasma chemistry capable of giving a scientific paper, because I do not believe that there are that many active researchers in

this country. Another factor is that the papers at the Tokyo conference were oral, and presented in English; It was almost certainly the case that many Japanese researchers active in plasma chemistry could not participate because they were not prepared to give their work in English. This dominance of the conference by the Japanese plasma community is, I believe, a warning to we in the United States that we are about to lose out in another field of future commercial importance if we do not produce manpower and support research in this area to a much greater extent in the future.

IMPLICATIONS OF THIS CONFERENCE FOR PLASMA RESEARCH AT UTK

I made the point above that the Japanese dominated this conference both in terms of attendance, and number of scientific papers presented on the program. My visit to Nagoya and other sites also indicated that the Japanese government is actively supporting a very broad-based program of plasma research both in the field of fusion energy, and in industrial materials processing and other industrial applications of plasmas. The proposed Institute of Plasma science at Nagoya will dwarf any similar national lab or university effort in the United States in the field of industrial plasma research. In talking with the participants and particularly the exhibitors at this conference, I got the strong impression that several areas of plasma science research were about to "take off" in terms of their annual cash flows and importance to industrial production.

One very active area at present is plasma-surface interactions such as those involving diamond deposition and plasma etching and deposition for

microelectronic circuits. It is my impression, however, that this is an area which we at the UTK Plasma Science Laboratory are not well equipped to enter, and as an institution, we will probably either have to pass up that entire area, or hire a nucleus of faculty to interact with Oak Ridge to build up an effort in that area. I see a much more hopeful picture in the area of thermal plasma research, including plasma arcs and plasma torches, for metal refining, plasma flame spraying, and metal cutting. In the United States, I understand that the annual cash flow for plasma flame spraying is approximately half a billion dollars a year, with three hundred million of that being military and aerospace applications, and two hundred million being other civilian applications. A similar level of activity seems to exist in Japan, since most of the Japanese exhibitors at this conference offered plasma flame spraying equipment.

During the discussion periods in the sessions on thermal plasma research, there was a repeatedly expressed impression that thermal arc research was about to "take off" and find major industrial applications in replacing electric arc furnaces with heating processes based on plasma torches. This area of application has an enormous industrial potential since, worldwide, about two hundred million tons of steel is made every year with electric arc furnaces. The very crude level of theoretical understanding of the physical processes in thermal plasmas also implied a good opportunity for academic research input, particularly by groups like ours at the UTK Plasma Lab that are familiar with the academic and fusion-related plasma physics that has been developed over the past 20 to 30 years.

The opportunities for UTK in the field of thermal plasmas are indicated by the very small representation of papers in this area from the United States. There were only 37 US participants registered at this meeting, many of whom were involved in plasma-surface interactions of a kind used in the microelectronics industry. A careful survey of the papers presented by the 37 US participants at this conference indicates that 20 of the 37 were interested in the thermal plasma area, and the remaining 17 in plasma surface interactions and microelectronic applications. Of these 20 individuals in the thermal plasma area, 12 were from 7 universities in the United States, and 8 were from industry. Of the 7 universities represented at this meeting, 6 were represented by a single individual (including myself as the representative of UTK). The seven universities represented in the thermal plasma area at this meeting included Georgia Tech, SUNY at Buffalo, Florida State at Tallahassee, The University of Minnesota (6 representatives) Stanford University, UTK at Knoxville (myself), and Western Illinois University. It is a curious fact that none of these universities are very active in the DoE fusion program; there seems to be a pattern by which universities that are funded in plasma research either work for the DoE, or for other agencies that fund thermal plasma research; but not both together. The six universities that sent only one representative to this meeting have very small efforts in the thermal plasma area, which typically involve a single senior faculty member and perhaps a couple of graduate students. All of these US university efforts in thermal plasmas, except that of the University of Minnesota, are small enough that we can reasonably expect to equal and exceed their level of effort in a matter of a few years if we choose to make the effort to do so.

In addition to thermal arc research at the UTK Plasma Science Laboratory, other opportunities for UTK involvement became apparent at this meeting. In the open forum at the end of the afternoon session on thermal plasmas, there was much discussion about the power supplies required for plasma torches and thermal plasma research. One member of the audience, who has been in the field for many years, raised the question "Why are power supplies still so expensive? There has been a tremendous advance in solid state control technology over the last 20 years, but we still seem to be paying the same number of dollars per kilowatt and using the same technology for our power supplies that we did 20 years ago". This, I thought, was a very fair comment. Discussions later with representatives of the plasma flame spraying companies among the exhibitors indicated that none of these companies have devoted any significant amount of effort to advancing the state-of-the-art in DC power supply technology of a kind that is needed in thermal arc research. I think there may be some major opportunities here for the UTK Instrumentation and Controls Center, and/or the Power Electronics Center, to design cheaper and better controlled DC power supplies for multi-kilowatt thermal plasma applications.

COMMERCIAL EXHIBITS AT CONFERENCE

One of the eye-opening features to me was the large number of exhibitors at this conference-about thirty-who offered high tech, off the shelf equipment for commercial plasma processing applications. This number of exhibitors was all the more surprising in view of the location of this conference in Tokyo, well away from the home base of many American and European

manufacturers. About half of the 30 exhibitors were Japanese companies. The most common product offered was plasma torches for plasma flame spraying. I remarked previously that in the United States there is about half a billion dollar cash flow in the plasma flame spraying business, and it was perhaps appropriate that plasma flame spraying equipment was offered in the largest variety. Each company seemed to have several models of plasma flame spraying equipment operating at different power levels, ranging from a few kilowatts to more than 100 kilowatts per unit. Several companies specialized in powders for plasma flame spraying. This area is apparently one in which there is much black art in the preparation of powders which will produce a uniform and reproducible coating under assembly line conditions. There were examples of plasma flame sprayed products from medical implants, to pots and pans for the average consumer. There were several manufacturers of diagnostic and process control equipment used on assembly lines for microelectronic circuit fabrication involving plasma etching and deposition. Several manufacturers offered plasma torches which were intended to replace the three phase electrical arcs currently used in the melting and refining of metals. The manufacturers of these plasma torches were optimistic that plasma torches would shortly replace AC arcs in the steel industry. Their optimism was supported by a paper from the Krupp Steel company, reporting the successful use of plasma torches in a 50 megawatt arc furnace at one of their German steel mills. This plasma torch offered many advantages, including longer life of the electrode and easier control of the power input to the melted metal. One of the major exhibitors at this meeting

was the Plasma Energy Corporation of Raleigh, North Carolina, which offered one of the largest product lines of any of the exhibitors.

TECHNICAL SESSIONS OF CONFERENCE

This conference was organized to last from 9:00 A.M. Monday, August 31 to 5:00 p.m. Friday, September 4. Sessions were scheduled for mornings and afternoons, with no scheduled activity over the noon hour on any day, and no evening activities scheduled for Tuesday, or Wednesday, evenings. On Monday morning there were three plenary lectures, the first by Prof. I. Tanaka, President of the Tokyo Institute of Technology, who spoke on the subject in which he made his professional reputation, "Control and Diagnostics of Reactive Plasma by Photochemical and Photoionization Techniques". This was followed by Prof. E. Pfender of the University of Minnesota, who spoke on "Thermal Plasma Processing in the 90's" and then by Dr. H. F. Winters from the IBM Almaden Research Center, San Jose, California, who spoke on "Low Pressure Plasma Science; a Discussion of the Present Status and Future Goals". These three one hour plenary lectures were the only ones of their type in the entire conference, all other oral and invited papers being presented in simultaneous sessions.

The conference contained both poster and oral contributed papers, but the conference organizers adopted the very peculiar arrangement of presenting all 172 poster papers on Monday evening, starting at 6:00 p.m. This made a very busy first night, with a combined reception, social hour and scientific session. It was very hard for anyone to see all of the poster papers that might have been of interest to him in the relatively short time allowed on Monday evening. Another serious problem with the Monday evening poster

session was that most of the non-Japanese papers were presented in that one session. Of the 172 poster papers, probably 90% were presented by non-Japanese. I am not sure whether this resulted from a decision of the local program committee, or whether it resulted from the desire of Japanese authors to give oral papers and foreign authors to give poster papers. In any case, putting all of the poster papers on Monday evening tended to make the remaining four days of the conference almost a purely Japanese event, a rather unfortunate state of affairs because it would have been interesting to have both Japanese and foreign papers on the same topics in the same session.

In the mornings and afternoons of the remaining four days of the conference, there were usually four simultaneous sessions of contributed oral papers. Within each oral session, one or two of the papers were invited and half an hour long, whereas the oral contributed papers were 15 minutes long. The Proceedings of this conference occupy four volumes with a total of more than 2500 pages. Extra copies of the conference Proceedings were $200 per four volume set, so I brought back only the set to which I was entitled as a conference participant. This is available in my office if anyone wishes further information on any of the papers that I describe.

On Tuesday morning, September 1, a session on metallurgy had several interesting papers. Donald R. MacRae of the Research Department of the Bethlehem Steel Corporation gave an invited paper on "Plasma Reactors for Process Metallurgy Applications". While it was being presented, there were over 110 people in the room with standing room only. This entire morning session was devoted to the application of plasma torches and arcs to melting and refining of metals in the steel and extractive metallurgy industry. Mac

Rae remarked that as an industrial person, he had problems looking for solutions and he pointed out that many plasma technologists claimed that plasmas were a solution looking for a problem. He felt that plasma processing could be used in extractive metallurgy to refine waste byproducts of metallurgical operations, but he made the point that plasma torches were only a part of the overall system in a steel plant, within which they must fit. He sees plasma processes as an option that has to be considered in upgrading existing metallurgical processes. He pointed out that plasma processing has been widely discussed in the last couple of years among individuals who are active in extractve metallurgy, and this visibility is leading to more serious consideration of their use in industrial processes.

A group from the University of Limoges, France, presented a paper on "Experimental Study of Transferred Arcs for Extractive Metallurgy", in which they also pointed out that transferred arcs are being used more and more in extractive metallurgy. They have developed long transferred arcs of up to 1.2 meters in length, and pointed out that both analytical theories which they developed and the actual practice of applying transfered arcs indicate that their operation is very sensitive to the design of the plasma jet. At this point I should point out that "transferred arcs" are arcs in which the electrical current path closes from the plasma jet or the arc electrode to the metal or material being heated or melted; and "non transferred" arcs are arcsin which the electrical current flows through an arc that is retained within the plasma jet, the current path of which does not close through the metal being melted.

A group from England presented a paper on a plasma process for the recovery of platinum metals from automobile catalysts. This paper was

devoted to the problem of extracting valuable metals such as platinum, from scrapped automobile catalytic converters. It was pointed out that catalytic converters are using at present one third of the total world supply of platinum. The richest natural platinum ore contains only seven parts per million of platinum, whereas the catalyst in automobiles typically contains a thousand parts per million. They developed a transferred arc furnace operating at 800 kilowatts that is capable of recovering platinum metals from scrapped catalytic converters.

The next paper in this session was by a group from France on "Control of the Plasma Refining of Materials by Computer Analysis Using an Optical Fiber Spectrometer." In this paper, a four megahertz inductive heating unit operating at 7 kilowatts, which was used for the purification of titanium and silicon, was monitored with a light pipe by the signal from the plasma above the melt. This light pipe technology had not previously been applied in this context, and they were able to make a case that it provided better control of the melting process.

The next paper in this session was by a group from Hydro-Quebec on plasma treatment of steel mill baghouse dust and recovery of metals, in which they described how they recovered lead, caesium, chromium, and other toxic heavy metals using a plasma reactor. They fed in dust containing these toxic metals, which had been generated in an electric arc furnace, and were able to extract them. The next paper in this session was from a group at McMaster University in Hamilton, Ontario and Ontario Hydro Research Corporation, in which they looked at the product gases formed by injecting powered coal and steam into the flame of a dc plasma torch. This was motivated by the desire to

obtain a natural gas substitute from coal. The next paper in this session was concerned with the refining of refractory metals by a 5 to 10 kilowatt plasma torch. A group from South Africa performed pilot-scale experiments in a plasma arc furnace at 120 kilowatts, which showed that the efficiency of utilization of electrical energy increased from 44 to 61% when the feed material was preheated to 700° centigrade in a fluidized bed reactor.

On Tuesday afternoon I attended the session on "Advanced Plasma Generators and Their Applications" which covered a number of papers on plasma arcs and torches and their applications to industrial processing. Dr. S. L. Camacho of the Plasma Energy Corporation in Rayleigh, North Carolina gave an invited paper on "Industrial Worthy Plasma Torches". He pointed out that plasma torches can be operated under conditions which are from 65 to 90% efficient in converting electrical power into thermal energy of hot or molten metal (the rest presumably goes into radiation and cooling water) and that plasma arc jets have been operated under water to a depth of 40 meters. In a second invited paper in the same session Masao Ushio of Osaka University spoke on arc discharges and electrode phenomena. He demonstrated that small amounts of oxygen in the gas of a welding arc caused small whisker-like tungsten dendrites to form, and these helped destabilize arcs which were operated in the presence of oxygen. He did a classic series of paired comparison experiments which showed with sectioned photomicrographs the growth of whiskers on the surface of electrodes which had been operated hot in an oxygen-containing atmosphere. The third paper in this session was a group from France who reported on a transferred arc furnace for refractory oxide treatment that is under development. They are

attempting to cast refractory oxides, such as aluminum oxide. They expect in the near future to try for continuous casting of this oxide in a 1 megawatt pilot plant. They observed an efficacy for aluminum oxide of 1.8 kilowatt hours per kilogram of cast material. A group from the University of Sherbrooke in Quebec reported on the electrical, thermal and powder melting performance of a 250 kilowatt dc transferred arc plasma furnace. They made the point that the power supply for this type of furnace must be chosen with care. They use a 230 volt, 1600 amp unit which produced heat fluxes of 0.4 to 1.3 megawatts per square meter. They used a fiber optic spectroscopic diagnostic and found that 50 to 60% of the arc power was available for heating the metal which they wished to melt. A group from the Nippon Steel Company of Japan spoke on the development of a tundish plasma heater (a tundish is a container which holds molten metal in a foundry or metal processing plant). They described various ways of using plasma torches to keep the metal molten until it was ready to be poured for casting or other foundry operations. The next paper was from the Krupp Steel Company in West Germany. It was significant because of the large scale of the plasma torch system which they used. They reported results from a 3.6 megawatt three phase plasma torch system operating at 600 volts and 6000 amperes. This was a 10 ton furnace which was heated by a 1.5 meter long arc. They expected this type of system to be used for tundish heating of storage vessels for iron before rolling or casting operations. Apparently it is possible to keep the temperature of the iron constant with this system, when this was not possible with conventional three phase arc furnace technology.

In the panel discussion which followed this session, It was pointed out that many industrialists are looking for plasma arc, plasma torch, and other plasma methods that can be applied to tonnage applications, and these are now in sight. As a result, many people in this field expect the use of plasma torches for metallurgical heating applications to greatly increase. The required dc power supplies currently cost about $100 per kilowatt, and those attending the session felt that these prices were too high. The general consensus during the panel discussions was that plasma torch furnaces would very probably replace conventional arc furnaces in the near future.

On Wednesday morning I attended a session on modeling thermal plasmas. The first paper was by Xi Chen from Tsinghua University in Beijing, China. He was concerned with finding a phenomenological heat transfer expression which would accurately predict the melting of fine powders in plasma torches used for flame spraying. He claimed to have come up with such an expression after an elaborate mathematical curve-fitting procedure which yielded a good fit above 7000 degrees Kelvin and even for conditions of free molecular flow. A group from the University of Sherbrooke in Quebec modeled the thermal behavior of powders in a plasma jet under dense loading conditions of a kind that can occur in plasma flame spraying applications. The axial electron temperature profile was not well reproduced by their model, and they also got very poor radial electron temperature profile agreement, a factor which they said might be due to fluctuations in the plasma parameters. Their model was essentially steady state.

I then moved over to a parallel session on surface interactions, in which the plasma sintering of carbide ceramics was discussed. There are two

Japanese papers on the subject on pages 1632 and 1638 of the Proceedings. It was reported that silicon carbide could be sintered successfully to the theoretical density by an RF thermal plasma. They used an RF power between 3 and 15 kilowatts, and sintering durations between 15 seconds and 10 minutes. In a second paper it was reported that compacts of 30 and 5 square meters per gram powders can be sintered within 60 seconds to 96% of the theoretical density in plasmas.

On Wednesday afternoon, September 2, I attended the session on modeling thermal plamas. The first paper by A. Kanzawa from the Tokyo Institute of Technology concerned the processing of thermal plasma flows in a tube. The situation being modeled was a prototype of the plasma flame spraying application where one of the chief issues is the very high heat flux to the wall. His paper contained both a theoretical analysis and experimental data to back it up, including measurements of heat fluxes of 10 megawatts per square meter at the nozzle. He found that a hot boundary condition, a hot ceramic tube surrounding the plasma jet, resulted in higher gas temperatures in the plasma jet itself, as opposed to the situation which existed with a mixture of cold air at the boundary of the jet. Another paper, also from the Tokyo Institute of Technology, was on the characteristics and magnetic control of a plasma jet by parallel magnetic fields. This plasma jet was operated at reduced pressure, about 8 to 40 microns, with a helium-argon mixture as the working gas. The objective of in this paper was to determine the effects of a stabilizing magnetic field on the operation of such a plasma jet. Not surprisingly, they found that the jet diameter decreases with increasing magnetic field, and that by having the magnetic field lines diverge like a

magnetic nozzle, the energetic charged particles will be carried to where the magnetic field lines intersect the wall, the hot neutral component continues down the axis. They also reported subtle differences in the attachment point of the arc between the anode and cathode, which they felt would lead to more efficient heating of the neutral gas with the magnetic field present. There was another very interesting paper by T. Watanabe of the Tokyo Institute of Technology on "The Fluid Dynamic Control of a Plasma Energy Flow by a Blowing Gas". This was another paper in which an elaborate analytical theory was backed up by experimental data. The object here was to achieve a greater or lesser concentration of flame sprayed materials throughout the diameter of the jet by adjusting the flow of gas at the plasma boundary. There were several other theoretical papers at this session on the modeling of plasmas in thermal arc jets, with attempts made to understand observed radial density and temperature profiles, and to manipulate these profiles in a way which is useful in plasma flame spraying applications. All of these models assumed that the plasma jets were axially symmetric and steady state; in acutal fact, the plasma jet itself is like a rotating spoke of plasma which thrashes around in the azimuthal direction in a way that is nonstationary and nonaxisymmetric. The experimental data taken to compare these plasma models with experiment all use steady state diagnostics which average over the plasma diameter and time in such a way that the plasmas appear to be axisymmetric and stationary. At the end of this session S. L. Camacho of the Plasma Energy Corporation gave a paper on the reversed polarity plasma torch, a device which that company is marketing and which was displayed by the Plasma Energy Corporation at the meeting exhibit. He pointed out that

in the reverse polarity plasma torch, the rear most of the two axisymmetric electrodes is the anode and connected to the positive pole of the dc power supply, contrary to the arrangement in most plasma torches. He discussed the way in which these kinds of torches can be operated as transferred or non transferred arcs.

On Thursday morning, September 3, there was a session on electron cyclotron resonance and magnetomicrowave plasmas for industrial applications in which my paper was scheduled. The first paper in this session was an invited review paper by K. Suzuki on microwave plasma etching. He made the point that in plasma etching applications, microwave power is produced by a magnetron under non-resonance conditions. This power typically produces electron energies as high as 100 electron volts, but with bulk electron energies between 3 and 10 electron volts. These magnetron generated plasmas can be used for plasma etching and offer the advantage of higher densities, a wide range of pressures over which they can be operated, and minimal surface contamination. It is expected that submicron etching scales of size should be possible using this method. He showed an example of a plasma etching cross-section, in which structures approximately 1 micron high and only 0.3 micron wide had been made with microwave plasma etching. The paper by myself and Mounir Laroussi entitled "Plasma Heating by Collisional Magnetic Pumping for Possible Low Pressure Industrial Applications" was next. In this, we used the analytically derived plasma heating rates to suggest that collisional magnetic pumping be used to superheat plasmas at low pressure for industrial processing applications. I was very surprised at the degree of interest in our paper. Perhaps because the

subject was entirely novel to the audience, the lecture room had standing room only and people standing outside the doorway. After presenting this paper I had a great many interested inquiries, and I gave away all 30 copies of the Proceedings paper which I brought along for distribution. The reaction to my paper at this conference suggested that we already have something at the UTK Plasma Science Laboratory to contribute to this field, if we choose to enter the plasma processing and plasma chemistry field. The paper following mine was on reactive ion beam etching using a selective gallium doping method. This was an advancement in standard reactive ion etching technology in which the generation of energetic ions in the sheath between the microwave generated plasma and the surface being bombarded produces energetic, unidirectional ions which allow submicron etching scales to be achieved. The fourth paper in this session was by Y. Sakamoto et al. on the erosion of graphite by very low energy hydrogen ions, an issue in plasma etching work. They investigated an electron cyclotron resonance plasma in which the graphite was eroded by neutral hydrodgen atoms of about 1 eV. The remaining papers in this session were fairly conventional papers on plasma etching using microwave generated plasmas.

On Thursday afternoon, September 3, there was a special symposium in response to the recent development of high temperature superconductors entitled "Plasma and Ion Processes for High Critical Temperature Superconductors". This session consisted of seven papers describing the attempted formation of films of superconducting material by plasma deposition techniques. I attended one or two papers in that area and also some papers in the parallel session on diagnostics of thermal plasmas which was of

interest to me because I wanted to obtain a feeling for the state of the plasma diagnostic art for thermal arc plasmas used for industrial applications. There was a very good invited review paper by V. Helbig from the University of Kiel in Germany on the diagnostics of thermal plasmas. In spite of its general title, it was restricted to spectroscopic diagnostics almost exclusively, and more particular than that, his paper was concerned with the assumption of thermodynamic equilibrium that is usually made in order to do spectroscopic diagnostics of such plasmas. This invited review paper left me, probably unfairly, with the impression that those who are researching thermal arc plasmas are relying far too much on spectroscopic diagnostics and the assumption of thermodynamic equilibrium. His paper was followed by a second invited paper by H. Haraguchi from the University of Tokyo, who spoke on inductivly coupled plasmas in analytical atomic spectrometry. This was a paper for people in the analytical chemistry field concerned about the influence of the arcs used to generate excited states, on the spectroscopic techniques used to identify unknown compounds and elements. The third paper in this diagnostic session was by T. Sakuta and M. I. Boulos from the University of Sherbrooke on "Simultaneous Inflight Measurements of Particle Velocity, Size, and Surface Temperature under Plasma Conditions". This was a very interesting paper, and while the diagnostic method was not very sophisticated, it allowed them to measure the size of solid and molten particles in the jet of plasma flame spraying devices. They used a microscope columated to view across the diameter of a plasma jet, and focussed so well that they could measure the passage across the field of view of very small droplets in the range of 50 to 150 microns. By looking at the passage of the

droplets interrupting a beam of light, they were able to measure the diameter of the particles. The measurement of such passages at two stations allowed the velocity along the axis of the jet to be measured. I gathered from their presentation that this diagnostic, although it is very simple in principle, had not been previously applied. They used it to determine the distribution of velocities, diameters and temperatures of the particles. The temperature data was obtained by looking at the emission of a particle as it filled the field of view. This same group also presented the next paper, which was a novel method of determining the temperature of heavy particles in a RF plasma using the OH molecular bond. This apparently had not been done previously, but it requires the OH bonds in order to work. The next to last paper of this session was by T. Nakanaga and colleagues from Japanese industry on "Diagnostics for an RF Thermal Plasma by Means of Optical Spectroscopy", The diagnostic technique which they reported was quite conventional, but I was very interested in their remark that they observe plasma fluctuations, which they mentioned as a problem, and which were about 30 to 40% of the rms value of the light intensities which they observe. This, along with a wide variety of similar data, indicates that one cannot understand these thermal plasmas without looking very carefully at the time series of the fluctuating quantities.

On Friday morning, September 4, I attended the "Session on synthesis of Ultrafine Particles". Plasma torches and related plasma techniques are often used in the formation of micron or submicron particles used in sintering fine ceramic shapes, or for producing the fine powders needed for plasma flame spraying or other applications. The sessions started with an invited paper by

T. M. Meyer of Alcoa Laboratories, who pointed out that quality control is a key to advanced ceramics. One way of achieving such quality control is to produce the fine powders by the plasma related technique of melting a material and having fine droplets condense out. He reported on the operation of a DC plasma pilot plant which was operated to produce high quality silicon carbide and titanium diboride powders. The powders were synthesized from the interaction of a plasma heated hydrodgen gas stream to produce powders from 0.3 to 1.5 microns in characteristic size. He reported that such powders have been sintered to densities near theoretical densities for silicon carbide, while maintaining a grain size less than 10 microns. This investigation was an example of black box physics, with no attempt having been made to model the physical processes in the plasma reactor. They apparently can make about 10 kilograms per hour of fine titanium diboride powder with their pilot plant and about 7 kilograms per hour of silicon carbide powder. The second paper in this session by R. Shimanouchi and colleagues from Osaka University reported the synthesis of titanium disulfide in the form of a fine powder prepared by plasma chemical vapor deposition. These powders were intended for the electrodes of a lithium battery producing 2.2 volts. This work was submitted as a master's thesis at Osaka University, another example of the close ties between industrial plasma interests and the research programs at many Japanese universites. The third paper at this session by M. Ashida and colleagues at Kobe University was on the preparation and properties of zinc containing, plasma formed particles. In this case they used a 13.5 megahertz electrodeless RF plasma to produce zinc particles whose characteristic dimensions were in the submicron range. When prepared in

argon gas at pressures of about a quarter of an atmosphere, the zinc particles were very regular in shape, having cross sections that looked like hexagons or squares. Under other operating conditions, the zinc particles looked like three dimensional snowflakes with many fine, needle-like structures pointing out in all directions. Several other Japanese papers were presented at this session, all of which used closely related techniques and seemed to get very similar results.

On Friday afternoon I attended several of the papers in the plasma spraying session. The first paper at this session was by a group from Sherbrooke University in Quebec, on "The Influence of Stabilized Zirconia Powder Characteristics on Particle Melting, Spray Efficiency, and Physical Properties of Plasma Sprayed Deposits". This paper was a straight-forward example of black box physics in which the authors adjusted the various knobs available until they achieved a desired product. The second paper in this session was by S. Takeuchi and colleagues from the University of Tokyo, who reported experimental measurements of RF plasma spraying. They used an RF-energized flame spraying apparatus in which there was a swirled vortex-like flow that mixed the incoming powder with the hot gas from the plasma jet. They had very detailed two dimensional profiles, in the radial-axial plane, of the kinetic temperature of the gas, and the velocity of the swirling gas. Their data were quite detailed, and they were able to relate the characteristics of the flame temperature and swirling gas patterns to the nature of the material deposited on the surfaces of interest. The third paper in this session was by M. Fukumoto and colleagues from the Toyohashi University of Technology, on a comparison of plasma sprayed coatings obtained under low

pressure and atmospheric pressure. They operated a plasma flame spraying apparatus at pressures which ranged from atmospheric down to about one twentieth of an atmosphere. They found, not surprisingly, that the flame became longer along its axis as the pressure was lowered, and this also affected the nature of the material sprayed onto the substrate. The remaining papers in this session appeared to be very similar to the four that I just discussed, so I moved over to the session on diamond deposition which is one of the hottest topics in the field of plasma surface interactions. In these experiments, the investigators typically operate in an atmosphere of methane with a substrate temperature of arout 800° centigrade. They then create a methane plasma with RF heating, usually at 2.4 gigahertz, and processes in the plasma then form free carbon, which deposits on the heated surface to form a layer of pure diamond. The interest in diamond comes from several quarters. I did not hear anybody at this conference admit to a desire to make gem quality diamond; the interest appeared to arise from the physical properties of diamond which is an electrical insulator but a very good heat conductor, a heat conductor almost as good as copper. As such, diamond would be very useful as a sandwich material in microelectronic circuits which could keep the circuit elements on either side cool because of its high thermal conductivity. Other applications of diamond surface layers include coating the cutting edges of tools. One of the papers in the session was sponsored by one of the Japanese heavy machinery companys. The investigators were attempting to, and succeeding in, coating silicon carbide and tungsten carbide (which are used as the edges of cutting tools) to improve the wear characteristics of these materials. I think it is probably significant that the 8

papers on diamond deposition were all Japanese, and all used almost identical techniques of depositing carbon on a heated substrate in conjunction with a microwave plasma, in most cases produced by microwave power at 2.4 gigahertz, the characteristic frequency of microwave ovens. I got the impression that almost anybody could create diamond coatings if only they had a small vacuum bell jar and a microwave oven to work with. A typical deposition rate for these experiments was about 5 microns per hour of surface buildup of the diamond layer; this buildup rate apparently was not an inherent limitation but simply a result of the fact that all these investigators used similar microwave power levels, similar pressures and otherwise very similar operating conditions. Several of the authors at this session showed what looked to me like very unusual photomicrographs, in which the diamond deposition process was interrupted at several points, and successive photomicrographs showed the buildup of the diamond layer with time as the sample was exposed to the methane plasma. All of these Japanese papers were delivered in English, and during the questioning I did not once hear any of them appeal to proprietary restrictions to avoid answering a question.

VISITS TO JAPANESE PLASMA SCIENCE LABORATORIES

During the second week of my trip, from September 7 through September 11, 1987, I visited four Japanese plasma laboratories in four different cities. These included the Institute of Space and Astronautical Science in Tokyo on Monday, September 7; a trip to the Nagoya Institute for Plasma Physics on Tuesday, September 8; a visit to the Plasma Physics Laboratory at Kyoto University on Thursday, September 10; and a trip to the JT-60 Tokamak facility in Naka, on Friday, September 11, 1987. In all cases except my visit to the JT-60 site, I made arrangements in advance with individuals already known to me professionally through meetings and correspondence.

Visit to to the Institute of Space and Astronautical Science

My contact at the Institute of Space and Astronautical Science (ISAS) was Prof. Kyoichi Kuriki, a senior individual whose research on arc jets for space propulsion had been familiar to me since a visit he made to the NASA Lewis Research Center in 1971. I was interested in meeting with Dr. Kuriki because of his 20-year continuous involvement in arc jet research for space propulsion, and also because of the many innovative diagnostic methods and approaches to arc jet studies which he had made over the years. His group is probably one of the oldest continuously active research groups in the arc jet field in the world; Most such research in the United States was dropped by NASA in the mid 1970's, and continuous funding in this area has been very hard to come by for other research groups.

In setting up a meeting, I anticipated that some of his work motivated by application of arc jets to propulsion would be relevant to space plasma torches

and thermal arcs of commercial or industrial importance; After being informed in detail of the many contributions of his group to this area of space propulsion over the last 10 years, I concluded that this was correct, and was surprised to find that neither he nor any member of his group is working on industrial applications of thermal plasmas. In addition, they do not have particularly close contacts with industrial plasma science or industrial research.

The Institute of Space and Astronautical Sciences underwent a major reorganization approximately three years ago. Prior to that time, it was an institute attached to the University of Tokyo and funded through that university by the Japanese Ministry of Education, Science, and Culture. At that time it was split off and funded as a separate institute, still by the Ministry of Education, Science and Culture, but is no longer attached administratively to the University of Tokyo. As a part of this reorganization the ISAS is being moved physically from its Tokyo campus to a site about an hour's distance outside Tokyo in the countryside; most groups within the ISAS had already moved out of the Tokyo campus at the time of my visit. Dr. Kuriki, his group, and the remaining groups on the Tokyo campus expected to move to the new location in Mombusho by January 1, 1988.

Dr. Kuriki and his group of students and postdoctoral associates have for 20 years been doing research on pulsed arc jets and plasma jets for space propulsion. Characteristically, these space propulsion systems are intended to operate on capacitor banks which are charged by electrical power from solar cells. The energy in the capacitor banks is transferred to propellent in pulsed arc jets. Kuriki has published extensively in the aerospace literature

concerning his pulsed arc jet work, and he has regularly travelled to the United States to present his work at the propulsion meetings of the American Institute of Aeronautics and Astronautics and at other aerospace-related international propulsion conferences. His group has apparently not been in contact with the plasma chemists (neither he nor any member of his group attended the International Conference on Plasma Chemistry in Tokyo the week previously) nor were they in contact with the industrial literature on plasma torches, arc jets and other devices very similar to the arc jets on which they had been working. The Japanese National Space Development Agency (JNSDA), which is the Japanese equivalent of NASA, expects to use the pulsed plasma jets developed by Dr. Kuriki and his group at the ISAS on a series of satellites for communications and scientific research, the first of which will be launched in 1992. At his laboratory at the ISAS, Dr. Kuriki has a number of moderate-size vacuum tanks, typically about a meter and a half in diameter and perhaps 2 to 3 meters long, in which pulsed plasma jets are tested, and he has a very large vacuum tank approximately 3 meters in diameter and 10 meters long, in which these plasma jets have been tested under simulated space conditions.

There is very little difference between the plasma parameters at which Dr. Kuriki's plasma jets operate, and those of industrial applications; the most important differences probably are that Dr. Kuriki's arc jets operate in a pulsed mode at reduced pressure, whereas most thermal plasma sources used for industrial applications operate in the steady state at atmospheric pressure. One of the major achievements of Dr. Kuriki's laboratory has been to develop a pulsed gas valve for the plasma jets which allow a measured amount of

propellent to be consumed at one time, and thus not waste the propellent at a time when it cannot be heated and exhausted at high velocity by the power source; beyond this, Dr. Kuriki and his students have made a number of other advances in the state-of-the-art. These advances include a segmented cathode to promote arc rotation and uniform distribution of the heat load at the electrode surfaces; and investigation of physical processes in the arc jet plasma by simulating an axisymmetric arc jet by a linear, two dimensional arc jet in which the segmented anode and cathode sections are lined up in a linear two dimensional array instead of an axisymmetric array. This allows them to make diagnostic measurements along the axis of the two dimensional arc simulation which are impossible in an axisymmetric geometry; It also allows high-speed photography of processes in the region between the arc jet anode and cathode using this two dimensional array, and studies of plasma fluctuations and turbulence far more sophisticated than have been made by anyone researching thermal plasmas for industrial applications. This group has also done plasma simulation studies of physical processes in plasma arc jets with a three dimensional software program more sophisticated than has been applied to industrial plasmas, and which yields good agreement with their own laboratory measurements of actual pla[illegible]ehavior.

When I visited the ISAS, I spent most of the morning in a seminar in which I presented some of our plasma turbulence work at the UTK Plasma Science Laboratory, and Dr. Kuriki and his senior graduate students reciprocated by showing me their recent experimental data. I was impressed by the depth and sophistication of their results, which were of a kind produced only by a research group of long standing. Because of the nature of his

financial support, the pressures on Dr. Kuriki have been to produce a useful electrical propulsion system for space, which he has done; the many related problems in thermal plasma research which affect industrial applications have had a minimal priority with them. Dr. Kuriki and his students have therefore tended to avoid meetings in the latter field at which it would have been appropriate to report their work.

I came away from my meeting with Dr. Kuriki and his students with a clear impression that they probably understand some of the physical processes in thermal arc plasmas much better than any other group in the world, and that there was a clear need to apply many of the approaches and methods which they have developed to plasmas of industrial interest. I brought back with me a large collection of scientific papers by Dr. Kuriki and his students, nearly all of it published in the aerospace literature, as a basis on which to build if we at the UTK Plasma Science Laboratory become involved in thermal arc research.

Visit to the Nagoya Institute of Plasma Physics

On Tuesday, September 8, 1987 I visited the Nagoya Institute of Plasma Physics. This Institute was founded around 1960 and has been associated with Nagoya University in Nagoya, Japan. Its initial mission during the 1960's and 1970's was as an institute for basic research in plasmas which related for the most part to fusion applications, or in a few instances, to astrophysical applications. This Institute has undergone a rather interesting development in the last 3 years. The emphasis of their research program has been shifting over this period from high temperature plasma physics and

fusion energy to industrially relevant plasmas, including plasma-surface interactions of a kind relevant to microelectronic circuit fabrication, diamond deposition, and other plasma-based materials processing research. Two of the IPP's major fusion research programs were terminated in December, 1986; one of these was the Nagoya bumpy torus, the last remaining steady state bumpy torus fusion experiment in the world. The second project to be canceled was their cusp-stabilized equivalent of the tandem mirror which uses radio frequency stabilized containment, called RFC-XX-M. Interestingly enough, the people and resources that were freed up by the termination of these fusion experiments were reallocated in two directions; some of them are working on diamond deposition and plasma surface interactions that are relevant to industrial applications; and some of the staff are working on a new fusion experiment, a large, small aspect ratio torsatron experiment that is a scale up of the Heliotron device at Kyoto University.

This transition at Nagoya from fusion to industrially related plasmas appears to have been prompted by funding pressures from the Japanese government. It is the policy of the Japanese government to create an entirely new fusion research institute about an hour's drive outside of Kyoto which will not be affiliated with any one university. This new Institute is to serve all Japanese universities and industries much like a national lab in the United States. This new fusion research laboratory is to have as its initial showpiece the scaled up, small aspect ratio Heliotron, for which the Institute of Plasma Physics at Nagoya, and Prof. Koji Uo's laboratory at Kyoto University will have joint responsibility. It is expected that over the next two to three years, the fusion -based plasma physicists at Nagoya will move out of the Institute of

Plasma Physics to this new research center. Some of the Nagoya plasma physicists will remain behind to do industrially relevant plasma science in what will be a new "Institute for Plasma Science" operating with the facilities and on the campus of the current Institute of Plasma Physics. The existing Institute of Plasma Physics is a separate campus about a half a kilometer from Nagoya University, and that university's engineering school; it has several high-rise office buildings and major, high-bay laboratories and altogether has facilities and floor space considerably in excess of our entire engineering school at UTK.

My contact at the Institute of Plasma Physics was Dr. Hideo Ikegami, who had been the Principal Investigator of the Nagoya Bumpy Torus project until its cancellation last December. He is now in charge of the scaled-up torsatron experiment that is to be sited at the new fusion research center. He informed me that the Japanese government had no intention of continuing with the bumpy torus line of research, but was interested in persuing alternate magnetic containment concepts such as the Heliotron/stellarator as alternatives to tokamak research. He himself is very interested in applying fusion-based plasma theory and diagnostic methods to industrially relevant plasmas, and he apparently is one of the prime movers in the conversion of the Institute of Plasma Physics into an industrially relevant Institute of Plasma Science. He was interested in our activities at the UTK Plasma Science Laboratory and was impressed perhaps more than he should have been by our brochure describing study and research at the UTK Plasma Science Laboratory. He remarked to me that he had been in the United States recently, attempting to make contact with university people who were active

in the field of industrially relevant plasma science, and had been largely unsuccessful. He stated that he was interested in initiating some form of collaborative effort with university-based plasma scientists in the United States, but that he was unsuccessful in setting up any such cooperative program because he could not find anybody to collaborate with! At this point I left open the possibility of future collaboration, but I did make it clear to him that our Plasma Science Laboratory at UTK was on a very small scale compared to the staff of hundreds of individuals currently affiliated with Nagoya's Institute for Plasma Physics.

I was shown around the Institute of Plasma Physics by Dr. Tatsuo Shoji, who was one of Dr. Ikegami's chief assistants on the Nagoya bumpy torus experiment. Since last December, Dr. Shoji has been involved with a diamond deposition experiment, using methods and apparatus left over from old fusion experiments. Dr. Shoji mentioned to me that by using a Lisatano-coil plasma source, and some electron cyclotron resonance heating (both methods which are common in fusion research but to my knowledge have not been applied by the industrial groups working on diamond deposition) that they had been able to achieve deposition rates of over 50 microns per hour, a deposition rate a factor of 10 higher than those reported the preceeding week at the Tokyo conference on plasma chemistry. I found it very interesting that Dr. Shoji and many other of the staff at Nagoya had turned their attention from fusion experiments that had been canceled last December to industrially relevant plasmas. To my knowledge, nothing like this has happened in any of the national labs in the United States that are doing fusion research. This is unfortunate for our country, because while the change in activity is hard on

people's careers, it is a very good way to assure that some of the methods developed in the fusion program are applied to industrially relevant problems. When Dr. Shoji showed me around the Institute of Plasma Physics, I saw several other research groups using some of the older apparatus from high temperature fusion experiments which were now being applied to problems of plasma surface interactions, or other industrially relevant research. Dr. Shoji expected tc be working on diamond deposition and other related problems until such time as the new small aspect ratio heliotron/torsatron was in operation at the new laboratory site.

Another interesting aspect of the tour at Nagoya was my visit to the research laboratories of the Nagoya University Engineering School. There is a tremendous amount of plasma related research at Nagoya University which is not related to the fusion research at the Institute of Plasma Physics. The engineering school research involves both undergraduate and graduate students, as well as faculty. This work is funded by the Ministry of Education, Science, and Culture of the Japanese government. None of the work which I was shown in the Nagoya University Engineering School has as its objective the advancement of fusion research or high temperature plasma physics; all of it was justified in terms of possible results in understanding plasma-surface interaction, plasma heating, and other forms of plasma materials processing. For example, I was shown the laboratory of Dr. Shuichi Takamura, who is on the electrical engineering faculty at Nagoya University. His lab has not one but <u>two</u> tokamaks and <u>two</u> <u>other</u> toroidal plasma experiments that are being operated, not for their fusion relevance, but as plasma sources to study plasma surface interaction.

From what Dr. Takamura and others had to say about the funding climate and the governmental motivation for funding their work, apparently for the last several years any proposal which involves an experimental bridging of tokamak of fusion research and industrially relevant plasma science is almost certain to be funded, regardless of whether it is the most efficient or effective apparent way of achieving the stated objectives. It seems that if proposals have the right number of fusion and industrial plasma processing buzz words in them, a proposal is almost assured to be funded. I cannot understand in any other way some of the very peculiar hybrids of fusion research and plasma science which I saw at Nagoya.

I visited the laboratory of Prof. Toshio Goto of the Department of Electronics at Nagoya University who, along with a student of his, Kyaw Tint, are both doing plasma surface interactions. Specifically, they are doing emission cross section work for plasma etching and deposition applications. In the United States the kind of work that they are doing would normally be done in a physics department concerned with gaseous electronics, but they were looking at some of the processes that can occur in microwave and dc glow discharge plasmas of a kind used in microelectronic circuit fabrication. They had a very well equipped laboratory that was turning out a large volume of relevant cross section data.

While at Nagoya I also visited Prof. Hideo Sugai, who was a Professor of Electrical Engineering at Nagoya. His research area is heating plasmas for industrial purposes. Hee expressed an interest in our work at the UTK Plasma Science Laboratory on collisional magnetic pumping. Dr. Sugai also had a couple of experiments on plasma-surface interactions which owed a

great deal to plasma heating and diagnostic methods developed in the field of fusion energy. Altogether I was very impressed by the breadth and scope of the activity in plasma science at Nagoya University. If their plans proceed to completion to form the Institute of Plasma Science which Dr. Ikegami described to me, they will have a single large institute or national laboratory with a staff of probably one to two hundred professionals beyond the doctoral level, all devoted to the industrial applications of plasma science. There will be no such comparable laboratory in the United States or, for that matter, in any European country of which I am aware. This Institute for Plasma Science would serve all Japanese universities, and it is intended to have close ties with individual academic research groups and universities all over Japan. These individual research groups in universities would be in addition to the central staff and laboratory facilities at Nagoya, which would be available to the university researchers on an "as needed" basis. With such resources and emphasis on plasma science in Japan, I expect that in the future they will beat the pants off of this and other countries in the industrial plasma processing areas which are going to be economically important in the future. The research done there already, in achieving diamond deposition rates as high as 50 microns per minute, is probably a small sample of what they can accomplish in the future. The researchers at Nagoya also seem to be much more flexible than those in the United States in their willingness to work back and forth between industrial and fusion related plasma physics. In this country, the very few individuals working on industrial plasma research and the national lab efforts on fusion energy not only do not communicate with each other, but each is either unwilling or unable to switch between fields

during fallow periods in their research. In the last decade, there have been major cancellations of fusion projects at the Los Alamos National Laboratory, at the Lawrence Livermore National Laboratory, at the Oak Ridge National Laboratory, and at Princeton. In no case, to my knowledge, have any of the staff freed up by these cancellations been reassigned to industrial plasma research.

Visit to the Plasma Physics Laboratory, Kyoto University

On Thursday, September 10, 1987 I visited the Plasma Physics Laboratory at Kyoto University, about a two and a half hour train ride West of Tokyo. My contact at the Plasma Physics Laboratory was Dr. Koji Uo. Dr. Uo is almost unique in Japan, having been an active researcher in fusion energy at least since 1960, and he is also probably the most original and creative of the Japanese researchers in this fie' As the initiator of the Heliotron series of experiments, which started about 1960 and continue to the present time with the Heliotron-E experiment, he is probably the only Japanese to preside over a magnetic containment experiment the basic concept of which evolved in Japan. Dr. Uo is remarkable in other respects also; he has the reputation of being an excellent and careful administrator of his laboratory, and is unusually conversant with the technology and operational details of the Heliotron experiment of which he is in charge.

The original Heliotron experiment of the early 1960's was a very different magnetic containment concept from the Heliotron-E experiment now in operation. Originally, the Heliotron was a toroidal picket fence concept, which looked like a toroidal array of magnetic cusps. The Heliotron

configuration of the early 1960's had the same relationship to the magnetic cusp geometry as the bumpy torus does to the magnetic mirror configuration; it was a toroidal array of magnetic cusps superimposed on a toroidal dc magnetic field. Over the twenty-seven year period since the initiation of the Heliotron series of experiments, the toroidal geometry has remained the same, but the details of the containment geometry have evolved in the direction of a torsatron-like configuration. The current experiment, the Heliotron-E, consists of a torsatron-like set of $\ell = 2$ helical windings, superimposed on a constant toroidal magnetic field generated by a separate set of toroidal magnetic field coils. It has been found that the toroidal magnetic field adds little or nothing to the containment of the Heliotron-E, and in recent years the Heliotron-E has been operated as an $\ell = 2$ torsatron. It is interesting that the Heliotron-E has been generating good plasma data for the last seven years, and its geometry and magnetic field strength are equal to or superior to the ATF facility which is scheduled to go into operation at the Oak Ridge National Laboratory in January of 1988.

The Heliotron-E device is very impressive. The magnetic field coils and helical windings are driven by large motor-generator sets capable of providing several hundred megawatts to supply the coils; there are up to 10 megawatts of neutral beam and ion cyclotron resonance heating shortly to be available in this experiment; and several hundred kilowatts of electron cyclotron resonance heating are also available. The resources devoted to this experiment are on the scale of a major national lab project in the United States such as the ATF or RFP, and the engineering and management of this experiment are superb. I was very impressed by the fact that Prof. Uo took the

better part of the day to show me around the facilities, of which he was justifiably proud. The experiment was in operation, and we got to see some of the data being processed and analyzed in the control room. Dr. Uo was very interested in and attentive to all the technological state-of-the-art details of the equipment which made up the facility; he took me through all of the transformer yards, equipment bays, power supply buildings, switch gear, etc., and pointed out to me all the advanced, state-of-the-art features of the equipment. So conversant was he with the operational details of the facility that he was able to open up the doors on equipment racks and point to specific pieces of solid state and control equipment to make various points about the engineering of the facility. I know of no other laboratory director who would be aware of which doors were interlocked and which not, and which piece of apparatus it was safe to show a visitor while the experiment was being run. Very impressive.

All of the Heliotron support facilities as well as the Heliotron device itself were made by Japanese industry, with the close collaboration of Prof. Uo and his staff. At least some members of his staff are working on the small aspect ratio torsatron/Heliotron which is to be built in collaboration with the Nagoya Institute of Plasma Physics, and sited in the mountains about an hour's drive from Kyoto. The Heliotron-E experiment was criticized for inadequate diagnostics shortly after it was first put into service in 1980. I saw no evidence of this lack of diagnostics when I visited. They have Thomson scattering, charge exchange neutral energy analysis, and all of the major high temperature plasma diagnostics except heavy ion beam probing in service at this time. The plasma parameters which were quoted at recent meetings and

which were quoted to me during my visit were extremely impressive. Most impressive was the product of number density and containment time, which was 10^{12} seconds per cubic centimenter at Ti = 2 keV, and 7 x 10^{12} sec/cm^3 at 500 eV = Ti. In this general area of ℓ = 2 torsatron research, I would say that at present Japan is at least 6 years ahead of us, even assuming that the ATF facility at Oak Ridge works as designed. The ATF has almost the same dimensions, aspect ratio, and magnetic field strength as the Heliotron-E, but will achieve a first plasma something like seven years or more after that of the Heliotron-E experiment.

In talking with Prof. Uo and his colleagues, I found that they are very well informed of progress at Oak Ridge, and of the theoretical results on stellarator and torsatron-like geometries which been published from Oak Ridge in recent years. In fact there is a active program of exchange of personnel, which is going to get into high gear when the ATF facility is first placed into operation in early 1988. While at Kyoto, I met Dr. Fumimichi Sano, who is going to be visiting the Oak Ridge National Laboratory for a period of about 6 weeks in the Spring of 1988 as part of the US-Japan cooperative exchange program.

Visit to the JT-60 Tokamak

One of the things that I wanted to see in Japan was the JT-60 tokamak, the Japanese equivalent of the TFTR tokamak in the United States, and the JET device in Europe. The arrangements for my visit were not complete at the time when I left for Japan, and so I had to phone the headquarters of the Japan Atomic Energy Research Institute (JAERI) to finalize arrangements on Wednesday, September 2. The headquarters of the JAERI are in an office building not too far from the center of Tokyo. I met Dr. Akio Kitsunezaki who is General Manager of the fusion program, and his assistant, Mr. Shuji Hino, who is deputy general manager of the Office of International Affairs of the JAERI. The problem with the arrangements was that apparently I was the first US plasma physicist who had ever requested to see the JT-60, who was not also a member of the US DoE establishment. Everybody who had come over there previously had arranged their visit through official channels in DoE's Office of Fusion Energy, and they were unsure how to proceed with a request from a private individual. Dr. Kitsunezaki was at one time the leader of the Doublet-III Japanese team that was collaborating in San Diego as part of the joint Japan-US program on Doublet-III research. I gave Dr. Kitsunezaki a copy of my textbook, Introduction to Fusion Energy, and mentioned that I was interested in visiting the JT-60 facility in part to get some photographs and other materials that I could include in the second edition. He and Dr. Hino were able to make very convenient arrangements for me to visit the JT-60 site on Friday, September 11, 1987.

On Friday, September 11, 1987 I traveled about an hour and a half outside of Tokyo to the JT-60 site which is located in a rural district called

Naka. This part of Japan is best reached by train, and the JT-60 facility itself is about 5 or 6 miles from the train station, very difficult to reach unless arrangements have been made in advance. Thanks to the efforts of Dr. Hino, I had a complete schedule arranged for me. When I arrived at the train station, I was met by an official car, and taken to the JT-60 site where I met the director, Dr. Masaji Yoshikawa and a number of his subordinates. The JT-60 site is located in the middle of a farming area, with almost no industrial or commercial development around it. There seemed to be no motels or hotels, and it would probably be a very difficult site to visit without some kind of formal arrangements. The cost of the over-all JT-60 facilities was probably more than half a billion dollars. It was built in collaboration with Japanese industry, with what appears to have been a suprisingly small staff of plasma physicists and engineers. The JT-60 facility was the first major facility to be located at Naka, but it will probably not be the last, since it is apparently intended that Naka be the location for future development of tokamak and/or fusion engineering test reactors. The Naka site is served by the main Japanese power grid, and in its size and scope appears to be significantly larger than either the TFTR or the JET facility.

In the morning I was shown the JT-60 tokamak itself, and some of the support equipment which is enormous in scale and very impressive. I was given a series of photographs and isometric cutaway drawings of the JT-60 which should be very useful for my fusion courses, and some of which I intend to include in the second edition of my textbook.

In the early afternoon, I had a seminar with the division chiefs and others who work under Dr. Yoshikawa. These included Mr. Masatoshi

Tanaka who is director of the Department of Thermonuclear Fusion Research, Dr. Shin Yamamoto, who is a member of the Department of Large Tokamak Research, and Mr. Tatsuoki Takeda, who is head of the Plasma Theory Laboratory. Others were in attendance, whose business cards I did not collect. I gave these men a brief summary of the findings of the recent National Academy of Sciences-National Research Council's Committee on Advanced Fusion Energy on which I had just served, and the report of which was being published at the time I was in Japan. They were interested in my remarks on advanced fusion fuels, a matter to which the Japanese apparently have given little if any thought at all. Their concerns at Naka were with the confinement time scaling of tokamaks (this concern is certainly not restricted to the Japanese!) and they were very interested in my past work on the electric field bumpy torus, in the work on electric field dominated plasmas which we have done at the UTK Plasma Science Laboratory, and also on our work on the effective collision frequency in plasmas which we have done also at the UTK Plasma Lab.

They apparently are undergoing a period of major reevaluation of the JT-60 design. The JT-60 tokamak was designed to operate on pure hydrogen, and not to burn deuterium and tritium to achieve scientific breakeven. The Japanese apparently felt that the radiological hazards of tritium and of dealing with an activated reactor structure were not worthwhile at this stage of fusion research, so they built the JT-60 to the same approximate size and magnetic induction as the TFTR tokamak, but they did not make any provision for remote maintenance or activation of the structure, which would had to have been done if they planned to burn tritium. The JT-60 design has a

major feature which is currently giving them a great deal of trouble, and which will apparently necessitate a major redesign and rebuilding of the entire facility before it can produce plasma densities, temperatures and containment times comparabable to the TFTR and the JET facility. The JT-60 tokamak was designed with a toroidal divertor, that is a set of diverted particle drift surfaces in the equatorial plane of the torus. These diverted drift surfaces, along which the escaping plasma, should leave the containment volume and go around the outer equatorial circumference of the containment volume into a dumping chamber. This dumping chamber is reached through a slot around the equatorial plane of the torus. This type of toroidal divertor made it impossible to insert diagnostic probes, diagnostic ports, and rf heating antennae in the equatorial plane of the torus. For this reason, the original design of the JT-60 had all of the diagnostic sight lines parallel to the major vertical axis of the torus, coming down vertically through the containment volume from top to bottom of the plasma. It apparently has become clear to them that they must have diagnostic access on the equatorial plane in order to make necessary profile measurements along the major radius. Moreover, the particular design of toroidal divertor which they incorporated into the JT-60 is not effective in removing impurities which are a particular problem with them. These impurities, and the nature of the toroidal divertor, apparently have kept the JT-60 tokamak from achieving the so-called "H-mode", a mode of good plasma confinement without which major tokamaks cannot hope to achieve scientific breakeven or their intended confinement times. Thus, while the enormous size, scope, and investment in the JT-60 facility were very impressive, it does appear to have a fundamental design flaw which must be

corrected at great expense and which will probably take one or more years. Only then will the JT-60 be fully competitive with major tokamak experiments such as the JET and TFTR.

APPENDIX K

Media Stories Featuring the AFOSR Research Program and the UTK Plasma Science Laboratory

Engineering wins Defense program

By Melanie Robinson
Daily Beacon Staff Writer

While some are criticizing research for adversely directing university energies outward, one UT professor is praising it for bringing resources into higher education.

Last week the electrical engineering department was notified of its selection to participate in the Department of Defense University Research Instrumentation Program. The department's request for $234,000 to buy research equipment was chosen from more than $1 billion in proposals from universities conducting research of interest to national defense.

J. Reece Roth, professor in electrical engineering, said the benefits reaped from research contracts has enabled his department to update obsolete equipment, thus increasing the value of the electrical engineering degree.

Until a few years ago the department was typical of others across the nation. But because of money received from research contracts and equipment donations from the Defense Department, the electrical engineering department has vastly improved its inventory, Roth said.

As a result of outdated equipment, many graduates received extra training from employers. Because the Defense Department hires many electrical engineering graduates, including UT's, the situation had to be remedied, Roth said.

"The problem got so bad five years ago Washington realized something had to be done. They instituted this program to bring their contractors up to date," Roth said.

In addition, the electrical engineering department receives free, slightly outdated research equipment from government labs and arsenals. The department has accumulated about $1 million in surplus equipment from the Defense Department.

Without the funds and equipment supplied through research contracts, Roth said his department would do without equipment vital to research because the university does not give ample support.

"UT gives us floor space, water and electricity. That's it," he said.

Roth said electrical engineering research contracts have brought in about $1 million dollars in recent years, but UT keeps a substantial portion to pay for secretarial costs and other expenses. When the department receives equipment grants, no overhead costs are kept by UT.

Most of the money from the new award will go to buy a $170,000 Microwave Network Analyzer.

Not only students will benefit from the new equipment, but also the community, Roth said.

"In addition to our students getting experience with state-of-the-art equipment, the technology of the whole area will be elevated because information will be carried to employers," he said.

A12 KNOXVILLE JOURNAL Thursday, March 13, 1986

CITY/STATE DIGEST

Air Force awards contract to UT

The U.S. Air Force has awarded the University of Tennessee's College of Engineering's Plasma Laboratory a $600,000 contract for research in plasma, fusion and microwave emissions. The research will include work toward the development of fusion energy, according to a university spokesman. The three-year contract also provides for undergraduate research assistantships in the summer.

Engineering Update
THE UNIVERSITY OF TENNESSEE, KNOXVILLE
COLLEGE OF ENGINEERING
VOLUME 3/ISSUE 1/WINTER-SPRING 198(

THE UTK PLASMA SCIENCE LABORATORY

Course offerings and active research in the field of plasma science ve been underway at The University of Tennessee, Knoxville, since 1970. The UTK plasma science laboratory was set up in its present form in 1980, within the electrical engineering department.

Since 1980, the laboratory has been partially supported by contracts with the Office of Naval Research, the Air Force Office of Scientific Research, the National Science Foundation, and the Tennessee Valley Authority. In calendar year 1985, the total budget of the UTK plasma lab was approximately $473,000. The laboratory focusses its research efforts on steady-state, electric field-dominated plasmas. Our emphasis on steady-state plasmas makes it relatively easy to take diagnostic data of high quality and to vary parameters in an exploratory way to identify and study the physical processes which occur in these plasmas. The emphasis on electric field dominated plasmas (those plasmas having strong radial and/or axial electric fields penetrating them) has allowed us to focus on an area of plasma science which has been neglected by other university research groups. Particular electric field dominated plasmas under study in the plasma science laboratory include the orbitron maser, which is of interest because of its capability to produce sub-millimeter microwave emission at power levels in excess of one watt; and plasmas generated by Penning discharges, which are highly turbulent and provide a convenient test bed for research on plasma turbulence and collisional magnetic pumping as a plasma heating technique.

The laboratory is equipped with a variety of operating plasma diagnostic instruments and a large inventory of power supplies, electronic test equipment, and communicaitons related electronic equipment which support our exploratory research efforts. There are also several inexpensive-to-operate steady-state plasmas on which diagnostic instruments can be veloped and debugged and on which data of unusually high quality n be taken with existing instruments.

The laboratory acquired in 1980 approximately $400,000 of plasma-related instrumentation from the NASA Lewis Research Center, which enabled us to begin our research program on electric field-dominated plasmas. This inventory of laboratory equipment has been supplemented over the last three years by used but serviceable surplus equipment obtained from Department of Defense installations.

A recent grant (FY 1985) of $233,000 from AFOSR under the DOD-University Research Instrumentation Program has allowed us to purchase state-of-the-art radio frequency network analyzers and electronic test equipment which not only provides our students training with the latest test equipment, but also makes it possible for us to take plasma diagnostic data of a quality and kind that is possible to very few other university based research laboratories.

The UTK plasma science laboratory now has one of the best-equipped university facilities in the country for the steady-state, quantitative measurement of plasma emissions over a wide frequency range, and for the measurement of plasma turbulence in the form of electrostatic potential and number density fluctuations over a wide dynamic range and over a wide range of frequencies. Our inventory of research equipment now includes computerized data handling and processing equipment which is connected to the electrical engineering department's VAX computer for on-line data analysis. Over the past five years, we have pioneered in the development of software programs for the analysis of data from Langmuir probes, retarding potential energy analyzers, charge exchange neutral energy analyzers, and electrostatic turbulence and microwave scattering data.

Oversight of the plasma science laboratory research is conducted by Professors J. Reece Roth and Igor Alexeff.

Context
THE UNIVERSITY OF TENNESSEE, KNOXVILLE

Roth, Alexeff Get $600,000 To Develop High Resolution Radar

Two UTK scientists—working at the frontiers of radar and communications research—have been given a $600,000 grant to pursue their studies about the way plasma affects microwaves.

For almost a decade, Dr. Igor Alexeff and Dr. J. Reece Roth have been studying microwave emissions generated when materials are superheated beyond the liquid and gaseous states to become plasmas. The material inside a fluorescent light tube is a plasma, as are the sun and all stars.

The three-year contract from the Air Force Office of Scientific Research will provide $200,000 annually for Alexeff and Roth, professors of electrical engineering, to do basic research that could lead to a new generation of high resolution radar and to improve communications between earth and voyaging space vehicles. Their work also has potential applications for fusion energy research, sophisticated welding and laser systems, and in the "Star Wars" defense plan.

Tim Elledge

Dr. Igor Alexeff

"Plasmas could be useful as a jamming tool," Roth said. "They produce a broad band of radio frequency emissions, all the way from the lower end of the AM radio band up to 1.2 gigahertz, which is far above most television channels."

Plasma is the key ingredient in what scientists view as the ultimate energy source—fusion. If a hydrogen isotope, found in seawater and called deuterium, is heated to the plasma state, it produces a tremendous amount of energy without the radiation side effect of fission nuclear reactors, Alexeff said.

Princeton University scientists have achieved fusion reactions for a few tenths of a second but do not yet fully understand how ions move in plasma. Once controlled fusion is developed, a reaction fed by seawater would be perpetual, like that of the sun, producing vast amounts of energy, the engineers say.

Alexeff and Roth, who have collaborated since 1978 in their Ferris Hall laboratory, also are interested in how plasmas block radio frequency waves and how signals might be pushed through them. Plasmas generated by the heat of reentry into the earth's atmosphere block communications from space vehicles.

"By looking at the way the radiation is absorbed," Roth said, "We can tell how frequently the electrons are colliding and how momentum, or energy, is removed from the electrons."

The grant also provides for summer internships each year that will permit nine undergraduate engineering and physics students to work in the Plasma Laboratory. Roth said the grants of $2,000 each were established to acquaint students with research so they might consider graduate studies after they receive their undergraduate degrees.

Tim Elledge

Dr. Reece Roth

tennessee news

Maser draws scientist across half a world

Chinese professor watches work at UT

by JAY DISKEY
News-Sentinel staff writer

J. Miles Cary /News-Sentinel staff

Liu Shenggang, Chinese scientist, is visiting the University of Tennessee.

Not many people travel halfway around the world to study synthetic atoms in a small metal cylinder, but Liu Shenggang did and he says it was well worth the trip.

Liu, a 53-year-old scientist from Chengdu, China, is visiting the University of Tennessee for two weeks to study Dr. Igor Alexeff's Orbitron microwave maser — a small metal device that is expected to usher in a new era in electronic communications.

The device may also spark an exchange of professors between UT and the Chengdu Institute of Radio Engineering, said Liu and Alexeff, a UT professor of electrical engineering who invented the Orbitron.

What Liu learns in Alexeff's Ferris Hall laboratory he will take back with him to Chengdu, the Chinese professor said.

"I'm very interested in the subject," Liu said of Alexeff's Orbitron maser. "Its applications are very wide."

Alexeff's maser — a microwave amplifier using stimulated emission of radiation — can produce microwaves of a higher frequency than had been thought possible before. Such waves are commonly used to transmit radio and telephone signals.

Military personnel and aviators are interested in the device because it will provide sharper radar images of objects. The Orbitron will also make for more compact radar units, said Alexeff, who is arranging for sale of the device to a commercial firm.

"It is the next generation of microwave tubes for radar," he said.

Earlier this week the Institute of Electrical and Electronics Engineers Inc. named Alexeff the outstanding engineer in the Southeast because of his contributions to microwave technology and the invention of the Orbitron. Alexeff is the founder of the Tennessee Inventors Association.

Liu, the youngest member of China's prestigious Academy of Science met Alexeff at a conference in Florida several years ago.

He had to obtain special permission from his government to travel to the United States to visit Alexeff at UT, he said. The trip took him a year and a half to arrange.

Since arriving at UT Liu has spent most of his time in Alexeff's lab. Before he leaves for California Tuesday he will lecture to physics and electrical engineering students at UT.

Liu said American students are active and energetic. "But they don't take as many classes as the Chinese students do," he said.

Liu teaches microwave electronics at the Chengdu Institute, which is located in southwest China about 1,500 miles from Beijing. The school has about 8,000 students.

Alexeff said he is hoping to set up a professors exchange between UT and the institute in Chengdu. The exchange will have to be approved by UT administrators, Alexeff said.

"This visit is a very good opportunity to promote future exchange," Liu said.

'Outstanding' engineers display their capabilities

By PETER SCHEULEN
The Daily Beacon

UT's electrical engineers were the most successful team at this year's Southeast Conference of the Institute of Electrical & Electronics Engineers, winning awards in all four fields.

The successful members of the Department of Electrical Engineering were presented awards last week in the IEEE lounge at Ferris Hall.

Igor Alexeff, who has taught at UT since 1971, received the Outstanding Scientist Award for 'outstanding contributions to microwave technology (Invention of the orbitron microwave laser device),' and his role as a founder of the Tennessee Inventors Association in 1983.

Buddy Lee was awarded as the Outstanding Student for his performance as the chairman of the IEEE chapter at UT.

Ali Keshavarzi, a senior in electrical engineering, won third prize in the Student Paper Contest with his paper on "Low-Frequency Continuity Equation Oscillations in Partially Ionized Gases."

Pit Crews, also a senior in electrical engineering, received third prize in the Hardware Design Contest, which required keeping a "Pathfinder" in track at the highest possible speed.

The IEEE, which was founded in 1884, is an international organization with 10 regions worldwide and three in the United States. The IEEE is a member of the American Association of Engineering Societies and its headquarters are located in New York.

With approximately 85 percent of its members living in the United States today, the institute's stronghold is still in this country.

UT belongs to Region III of the group as one of 27 schools in the Southeast. At this year's conference, which took place April 5-8 in Tampa, Fla., UT achieved its best performance since participating in the conference.

The theme of Southeastcon '87 was "The Renaissance of Research and Development."

Alexeff, who also received the Centennial Medal for IEEE performance in 1984, said that "UT is doing extremely well in the technical field. In engineering we have a number of excellent scientists and students."

Ali Keshavarzi, who also presented his paper last Monday, commented on UT's success, "I'm glad that I represented UT in this conference. As an international student (from Iran) with English as a second language, I'm happy to place in the paper competition."

THE DAILY BEACON

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Grants help profs in research

Ion implantation may protect tanks from corrosion

By MARY WAID
Daily Beacon Staff Writer

Two UT engineers are hard at work for the university and the U.S. Army.

J. Reece Roth and Raymond Buchanan, both professors in the College of Engineering, have been awarded a $20,000 grant from the Army Research Office.

The grant is to investigate whether plasma ion implantation can help prevent metal corrosion.

"The official starting date (of the research) was July 1," Roth said. "We were notified of the award about the third of June."

"This was a program called the Short-Term Innovative Research Program, which was sponsored by the Army Research Office," Roth said. "In our area, which was natural sciences, there were 199 proposals, but only four awards were granted... we are pleased that our submission was chosen."

Roth and Buchanan's idea of plasma ion implantation would be ideal for stopping corrosion in army tanks and battlefield equipment.

The method involves placing metals in plasma. The plasma is a hot, ionized gas. If the metal is at a high negative voltage, ions are drawn out of the plasma and are, in turn, implanted on the surface of the metal.

Corrosion usually is prevented by galvanizing or painting metal parts, but the materials that have to be used in these methods are not as durable as materials that corrode.

"It would be more expensive than painting or galvanizing... it would never be competitive on that level," Roth admitted. "However, it would be cheaper and more effective than ion beam implantation."

"It would be economically feasible, and it might make sense to use it on things such as gear teeth and turbine blades," Roth continued. "There are many such aerospace applications that would make it economical to use the plasma ion implantation because of the parts."

"The ion beam implantation can't be used on such things as gear teeth or screw threads... beam implantation is very expensive and its uses are limited. Plasma ion implantation can be used on small and complex surfaces," Roth explained.

"We're off to a satisfactory start," Roth said. "We already have a plasma apparatus set up and in operation. We have to make a few pieces of high voltage switching, and we hope to have some exposed by September 1."

"The work we are doing for the Army will be completed by December," Roth said. "After that, we will submit a proposal to the Army for a three-year study."

Roth and Buchanan will conduct these experiments at UT's Plasma Science Laboratory.

Context

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Can Plasma Ions Stop Metal Corrosion?

If two UT Knoxville engineers are successful, the U.S. Army may never again have to worry about corrosion in tanks and other battlefield equipment.

Drs. J. Reece Roth and Raymond Buchanan, professors in the College of Engineering, have been awarded a $20,000 grant from the Army Research Office to investigate whether plasma ion implantation will inhibit metal corrosion.

The work also is funded by UTK's Center for Materials Processing and the Department of Materials Science and Engineering.

The method involves placing metals in plasma, which is a hot ionized gas. If the metal sample is at a high negative voltage, this draws ions out of the plasma and implants them on the surface in a thin layer that prevents corrosion of the metal.

Corrosion is usually prevented by galvanizing or painting metal parts. When that is not possible, metals or alloys that inherently resist corrosion are used. The drawback is that materials often have to be used that, while resistant to corrosion, are not as durable or as hard as materials that corrode.

"Plasma ion implantation, at least for the forseeable future, would be expensive compared to simple methods such as painting or galvanization," Roth says. "But we think it does have promise for immediate application to things like gear teeth, screw threads and turbine blades."

Plasma ion implantation could replace a related process — ion beam implantation — used to protect metal surfaces of prosthetic implants such as artificial hip joints, Roth said.

"Beam implantation is very expensive and its uses are limited. It can't be used, for example, on small or complex surfaces like gear teeth or screw threads. Plasma ion implantation would be much cheaper and works on any electrically conducting surface," he said.

"This new method could be used in a variety of industrial and military applications," Roth said. "The materials that are used now are chosen not because they are best for the job, but because they are corrosion-resistant.

"The Army is interested in plasma ion implanation because it could eliminate corrosion on things like turbine blades, which are used in helicopters, light aircraft, and even some vehicles."

Roth, professor of electrical and computer engineering, and Buchanan, professor of materials science and engineering, will conduct experiments for the research at UTK's Plasma Science Laboratory, which is affiliated with the Department of Electrical and Computer Engineering.

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Briefs

UT professor is Inventor of Year

Igor Alexeff, professor of electrical engineering at the University of Tennessee, will be presented the Inventor of the Year Award by the Tennesseee Inventors Association at its March 18 meeting. Alexeff holds seven patents in the area of nuclear energy and microwaves. He also is the new president of the inventors group, which meets the third Saturday of each month at the Tennessee Innovation Center in Oak Ridge.